# GULF AND CARIBBEAN RESEARCH

January 2001

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# EFFECTS OF SALINITY ON DEVELOPMENT IN THE GHOST SHRIMP *CALLICHIRUS ISLAGRANDE* AND TWO POPULATIONS OF *C. MAJOR* (CRUSTACEA: DECAPODA: THALASSINIDEA)

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*ABSTRACT* Salinity (S) was abruptly decreased from 35‰ to 25‰ at either the 4th zoeal (ZIV) or decapodid stage (D) in *Callichirus islagrande* (Schmitt) and 2 populations of *C. major* (Say). Other larvae were maintained at stable 35‰ or 25‰ S throughout development. In *C. islagrande*, duration of ZIV did not vary among the stable salinities. However, a decrease of salinity at ZIV reduced the duration of this stage, suggesting that the S decrease could be a possible cue for acceleration of larval development. In the Gulf population of *C. major* duration of ZIV was significantly longer at stable 35‰ S than at stable 25‰ S; the latter equaled duration for larvae transferred from 35 to 25‰ S at ZIV. Development in the Florida Atlantic population of *C. major* was variable but similar at stable 35 and 25‰ S. In 2 of 3 such comparisons, larvae reared at a stable 35‰ S more often molted to a 5th zoeal stage and became deformed at D than those reared at a stable 25‰ S . *Callichirus islagrande* and the Gulf population of *C. major*, both of which inhabit lower salinity waters on the Louisiana coast, were more similar in larval responses to salinity than were the 2 populations of *C. major*. Adult habitat was a better indicator of larval response to salinity than was phylogenetic proximity.

## INTRODUCTION

In decapod larvae, salinity (S) may impact rate of development (Vinuesa et al. 1985, Sulkin and Van Heukelem 1986, Gonçalves et al. 1995), size (Johns 1981), and behavior (O'Connor and Epifanio 1985, Tankersley et al. 1995). Previous studies examined the effect of decreased S on decapodids to determine if such a change serves as a cue for settlement (O'Connor and Epifanio 1985, Anger 1991, Forward et al. 1994, Wolcott and Devries 1994). A decrease in S may be important to species that pass through zoeal stages offshore and subsequently settle as decapodids (=megalopae) in estuaries. In *Uca pugnax* (Smith), duration of the decapodid stage was significantly shorter at 20‰ S than at 30‰ S (O'Connor and Epifanio 1985). While a decrease in S from 35 to 26‰ was not found to decrease significantly the duration of the decapodid stage of *Callinectes sapidus* (Rathbun) (Wolcott and Devries 1994), a decrease from 35 to 18‰ S significantly accelerated molting (Forward et al. 1994). Larvae of *Eriocheir sinensis* H. Milne-Edwards reared at 32‰ S accelerated molting when moved to 20‰ S at the decapodid stage (Anger 1991). However, maintaining decapodids at 32‰ S or moving them from 32 to 10‰ S increased the duration of the decapodid stage.

Several studies have also examined the effect of S on the zoeal phase of development. Success of larval development in *Armases cinereum* (Bosc) depends on an estuarine-adapted 4th zoeal stage (Costlow et al. 1960); while the decapodid withstands a range of salinities, survival of the 4th zoeal stage is restricted to estuarine salinities. Slight to moderate decreases in S can accelerate the rate of zoeal development as in *Lithodes antarticus* Jacquinot (Vinuesa et al. 1985) and *Armases miersii* (Rathbun) (Schuh and Diesel 1995); retard development as in *Armases cinereum* (Bosc) (Costlow et al. 1960), *Panopeus herbstii* Milne-Edwards (Costlow et al. 1962), *Menippe mercenaria* (Say) (Ong and Costlow 1970), *Palaemonetes vulgaris* (Say) (Sandifer 1973), *Uca pugnax* (Smith) (O'Connor and Epifanio 1985), *Armases angustipes* (Dana) (Anger et al. 1990), *Eriocheir sinensis* H. Milne-Edwards (Anger 1991), and *Carcinus maenas* L. (Anger et al. 1998); or have no obvious effect as in *Palaemonetes vulgaris* (Say) (Knowlton 1965), *Cancer irroratus* Say (Johns 1981), *Necora puber* (L) (Mene et al. 1991), and *Menippe mercenaria* (Say) (Brown et al. 1992). In some species, development is shortest at intermediate salinities tested and somewhat retarded at extremes as in *Rhithropanopeus harrisii* (Gould) (Costlow et al. 1966, Gonçalves et al. 1995), and *Cardisoma guanhumi* Latreille (Costlow and Bookhout 1968). In *Macrobrachium nipponense* (De Haan) response of larvae to decreased S was shown to vary between populations (Ogasawara et al. 1979). However, most studies to date have examined the effect of S by maintaining larvae at a constant S throughout development.

In the genus *Callichirus*, larvae typically pass through 4 or 5 pelagic zoeal stages (ZI to ZV) before molting to the decapodid stage (D) (Strasser and Felder 1999a). Although D is usually thought to be receptive to settlement stimuli, previous studies have shown that settlement and development of *Callichirus major* (Say) are affected by cues received at the 4th zoeal stage (ZIV). The Gulf of Mexico and Florida Atlantic populations of *C. major* have been shown to be genetically distinct (Staton and Felder 1995), have different intertidal distributions (Felder and Griffis 1994), have morphological differences in their larvae (Strasser and Felder 1999a), and respond differently to settlement stimuli (Strasser and Felder 1999b). While ZIV plays an important role in settlement of both populations of *C. major*, this stage of *C. islagrande* (Schmitt) does not appear to respond to sand and adult-conditioned water (Strasser and Felder 1998, 1999b). The Florida Atlantic population of *C. major* inhabits waters of relatively constant 35‰ S. In contrast, the Gulf of Mexico endemic *C. islagrande* and the Gulf of Mexico population of *C. major* experience lower salinities which may range from 12-30‰ (Felder and Griffis 1994).

The present study was conducted to determine the effect of low (25‰) and high (35‰) salinities on numbers of instars and rates of development. The study included comparisons of decreased S effects during ZIV and D to determine whether S differentially accelerated molting.

## MATERIALS AND METHODS

### Experimental Protocol

Ovigerous females were collected by previously described methods (Felder 1978) from the bayward side of a barrier island (Isles Dernieres, LA; 29°03.8'N; 90°39.5'W) in March, April, August, and September 1997 for *C. islagrande* and the Gulf of Mexico population of *C. major*, and from a sand flat on the north side of Sebastian Inlet (Florida; 27°51.7'N; 80°26.8'W) in May, June, and July, 1997 for the Florida Atlantic population of *C. major*. Ovigerous females were maintained in 20-cm diameter finger bowls with daily water changes until eggs hatched. Animals from the Gulf of Mexico were kept at 25‰ S, while those from the Florida Atlantic population of *C. major* were maintained at 35‰ S to approximate the S experienced in the natural habitat. Seawater was taken from well offshore Louisiana and Florida, filtered through a 30-μm mesh, and aerated before use. Seawater at 25‰ S was made by diluting 35‰ S seawater with deionized water.

Upon hatching, ZI larvae were moved to individual compartments of a plastic tray and maintained at 27° C, on a 12 h light:12 h dark cycle, in filtered seawater of 35 or 25‰ S. Larvae (ZI to ZV) and decapodids were reared under 1 of 4 S protocols: a) 35‰ S throughout development to the first juvenile stage (J1), b) 35‰ S and moved to 25‰ S after the molt to ZIV, c) 35‰ S and moved to 25‰ S after the molt to D, d) 25‰ S throughout development to J1 (Figure 1). Once each day, animals were examined visually to assess their stage of development, moved to containers with new seawater, and fed freshly hatched *Artemia* nauplii (Great Salt Lake). For larvae placed in seawater that differed from S at hatching, the S was increased or decreased slowly 3 to 4 h before the experiment was initiated. In treatments with a decrease in S at ZIV or D (b and c), larvae were moved directly from 35 to 25‰ S and thus experienced an immediate shift in S. Each experiment began with 40 ZI larvae per treatment and all larvae remained isolated for the duration of the experiment. Each experiment, performed with larvae from the clutch of a single female, was repeated for a total of 2 clutches with both *C. islagrande* and the Gulf of Mexico population of *C. major* and 3 clutches with the Florida Atlantic population of *C. major*.
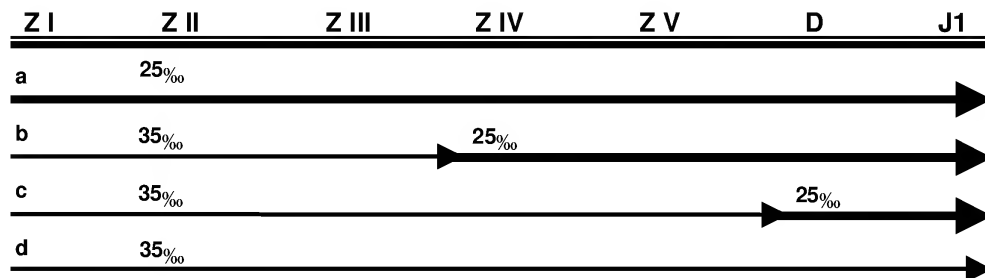


Figure. 1 Experimental treatments: a) 25‰ S throughout development to J1; b) 35‰ S from ZI to ZIII and moved to 25‰ S after the molt to ZIV; c) 35‰ S from ZI to ZIV and moved to 25‰ S after the molt to D; d) 35‰ S throughout development to J1. Thin line designates stages maintained at 35‰ S and a thick line designates stages maintained at 25‰ S.

**Analysis of data**

To determine if a decrease in S at ZIV or D accelerated development, the durations of these stages (in days) were compared between treatments with a 1-factor ANOVA (type III sum of squares). The Tukey-Kramer post hoc test was used to test for significance among treatments. Only animals that survived to J1 were used in comparisons of stage durations. Within each species (or population of *C. major*) durations of ZI, ZII, and ZIII were compared between animals maintained at 25‰ S (treatment a) and 35‰ S (treatments b, c, and d combined) with t-tests. The proportion of larvae that passed through a 5th zoeal stage (ZV) and the proportion of deformed decapodids were also compared between treatments with Fisher's exact-test. The term significant for all analyses is only used to describe differences in data sets that yield p-values < 0.05 with the statistical tests mentioned above. A resulting p-value ≥ 0.05 was considered to indicate that data sets did not differ significantly. Data were analyzed with Excel 5.0®, Super ANOVA 1.11®, and NCSS 6.0®.

## RESULTS

**Rate of development**

In *C. islagrande* and the Gulf population of *C. major*, durations of ZI, ZII and ZIII were typically longer in animals maintained at 35‰ S at these stages (treatments b, c, and d) than in animals maintained at 25‰ S (treatment a) (Table 1). In the Florida Atlantic population of *C. major*, durations of ZI and ZII were similar between animals maintained at both salinities; however, duration of ZIII was longer in animals maintained at 35‰ S than in animals maintained at 25‰ S, but this difference was significant only in Experiment 2.

The effect of S treatment on the duration of ZIV varied between species (Figure 2), but was found to be significant in experiments with both *C. islagrande* (1-factor ANOVA: Experiment 1, $F_{2,101}$ = 12.53; $P$ = 0.0001; Experiment 2, $F_{2,106}$ = 3.556; $P$ = 0.032) and the Gulf of Mexico population of *C. major* (1-factor ANOVA: Experiment 1, $F_{2,144}$ = 13.04; $P$ = 0.0001; Experiment 2, $F_{2,148}$ = 5.648; $P$ = 0.0043). However, there were differences between these species in the response of larvae to specific treatments. In *C. islagrande*, duration of ZIV was similar in animals maintained at a constant S from ZI to ZIV (either 25‰ S in treatment a, or 35‰ S in treatments c and d), but was much shorter in duration in larvae that experienced a decrease in S at this stage (treatment b).

Lower S also resulted in a shorter duration of ZIV in the Gulf of Mexico population of *C. major*. In both experiments with larvae of this population, the duration of ZIV was significantly shorter (Tukey-Kramer post hoc test, $P$ < 0.05) in animals maintained at a constant 25‰ S (treatment a) or moved to 25‰ S at ZIV (treatment b) than in larvae maintained at 35‰ S through ZIV (treatments c and d) (Figure 2). This differed from results with the Florida Atlantic population of *C. major* (Figure 2), wherein treatment did not have a significant effect on the duration of ZIV in Experiments 1 and 2 but was marginally significant in Experiment 3. However in

## TABLE 1

Mean duration in days (± SE) of ZI to ZIII for populations of *Callichirus* spp. maintained at 25‰ S (treatment a) or 35‰ S (treatments b, c, and d) from ZI to ZIII. Numbered experiments are for separate larval clutches. * = *P* < 0.001; ** = *P* < 0.05; with Student's t-test.

| | Number that reached J1 | | Mean duration ZI (SE) | | Mean duration ZII (SE) | | Mean duration ZIII (SE) | |
|---|---|---|---|---|---|---|---|---|
| Experiment | 25‰ | 35‰ | 25‰ | 35‰ | 25‰ | 35‰ | 25‰ | 35‰ |
| *Callichirus islagrande* | | | | | | | | |
| 1 | 31 | 74 | 2.00 (0.00) | 2.03 (0.02) | *2.03 (0.03) | 2.64 (0.07) | *2.55 (0.09) | 3.07 (0.06) |
| 2 | 35 | 80 | *2.37 (0.08) | 2.76 (0.06) | 2.06 (0.04) | 2.19 (0.04) | 2.37 (0.08) | 2.51 (0.06) |
| *C. major* (Gulf of Mexico) | | | | | | | | |
| 1 | 39 | 109 | **1.95 (0.04) | 2.05 (0.02) | *1.64 (0.08) | 2.00 (0.03) | **2.03 (0.06) | 2.24 (0.05) |
| 2 | 34 | 117 | *2.59 (0.09) | 2.99 (0.09) | 1.94 (0.10) | 1.88 (0.03) | **1.94 (0.07) | 2.13 (0.03) |
| *C. major* (Florida Atlantic) | | | | | | | | |
| 1 | 38 | 114 | 2.03 (0.03) | 2.02 (0.01) | 2.00 (0.0) | 2.01 (0.01) | 2.03 (0.03) | 2.08 (0.02) |
| 2 | 38 | 85 | 2.00 (0.00) | 2.01 (0.01) | 2.00 (0.0) | 1.98 (0.02) | **1.97 (0.05) | 2.12 (0.04) |
| 3 | 38 | 93 | 1.45 (0.08) | 1.59 (0.05) | 1.76 (0.07) | 1.77 (0.05) | 2.00 (0.00) | 2.11 (0.04) |
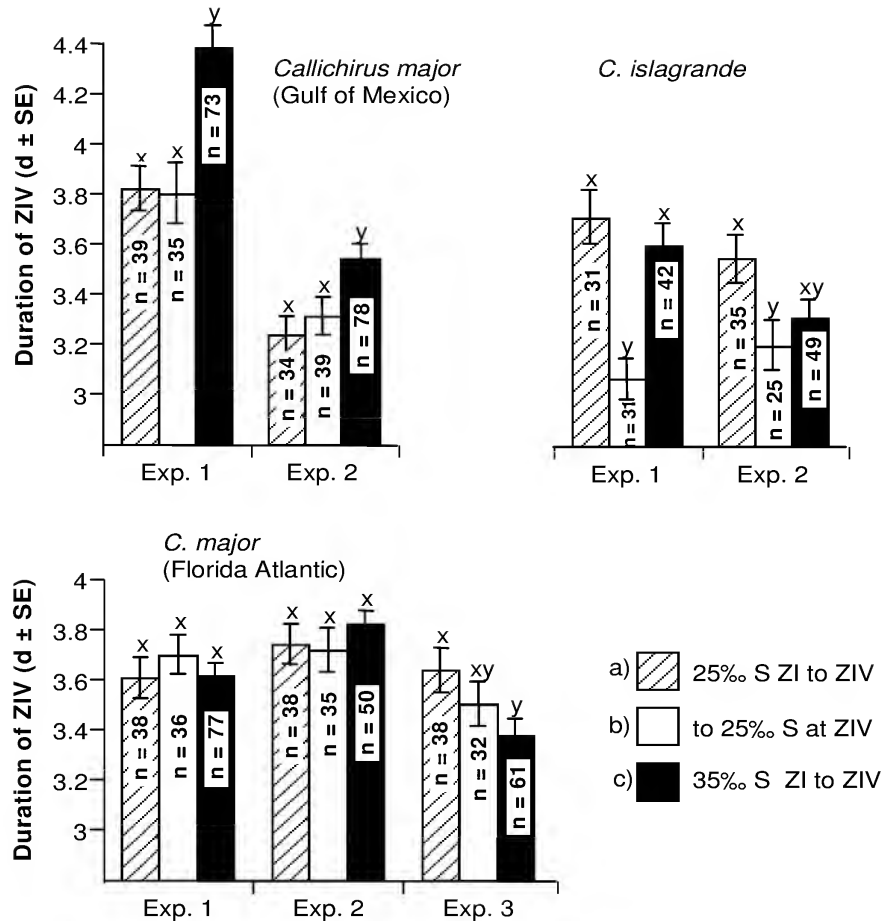
Figure 2. Mean duration in days ±SE of ZIV when larval stages were alternatively reared at 25‰ S from ZI to ZIV (treatment a), 35‰ S from ZI to ZIII but moved to 25‰ S after the molt to ZIV (treatment b), or 35‰ S from ZI to ZIV (treatment d), lettered treatments corresponding to those in Figure 1. Number of animals that reached J1 in experimental treatment is given within each bar. Means with different letters above the error bar differ significantly ($P = 0.05$) within the given experiment for that population with the Tukey-Kramer post hoc test.

this case, duration of ZIV was found to be significantly longer in animals maintained at 25‰ S (treatment a) than in those maintained at 35‰ S from ZI to ZIV (treatments c and d) (Tukey-Kramer post hoc test, $P < 0.05$).

Unlike the 4th zoeal stage, the decapodid stage was not affected by a S change in either *C. islagrande* or the Gulf of Mexico population of *C. major* (Figure 3). The duration of the decapodid stage also did not change significantly in Experiments 1 and 3 with the Florida Atlantic population of *C. major*, but treatment did have a significant effect in Experiment 2 (1-factor ANOVA, $F_{3,119} = 9.502$; $P = 0.0001$). In Experiment 2, the duration of D was significantly shorter in animals maintained at 25‰ S (treatment a), or moved from 35 to 25‰ S at ZIV (treatment b), than in animals moved from 35 to 25‰ S at D (treatment c), or maintained at 35‰ S (treatment d), with the Tukey-Kramer post hoc test ($P < 0.05$).

**Presence of a 5th zoeal stage**

All of the larvae from the Gulf of Mexico population of *C. major* molted directly from ZIV to D (no ZV). While larvae in Experiment 1 with the Florida Atlantic population of *C. major* also followed this pattern, larvae from Experiments 2 and 3 often passed through a fifth zoeal stage (Table 2). In Experiment 2, the percentage of larvae that molted from ZIV to D (no ZV) was significantly higher in animals maintained at 25‰ S (treatment a, 100%) than in the other 3 treatments (b, 67%; c, 20%; d, 35%) according to results of Fisher's exact-test. Cultures with a decrease in S at ZIV (treatment b, 67%) had a significantly higher percentage of animals bypassing ZV, than did those maintained at 35‰ S through ZIV (treatments c, 20%; and d, 35%). In Experiment 3, significantly more larvae molted directly from ZIV to D in animals maintained at 25‰ S (treatment a, 90%) than among the other 3 treatments (b, 54%; c, 36%; d, 42%). Passing through a 5th zoeal stage reduced survival. Most
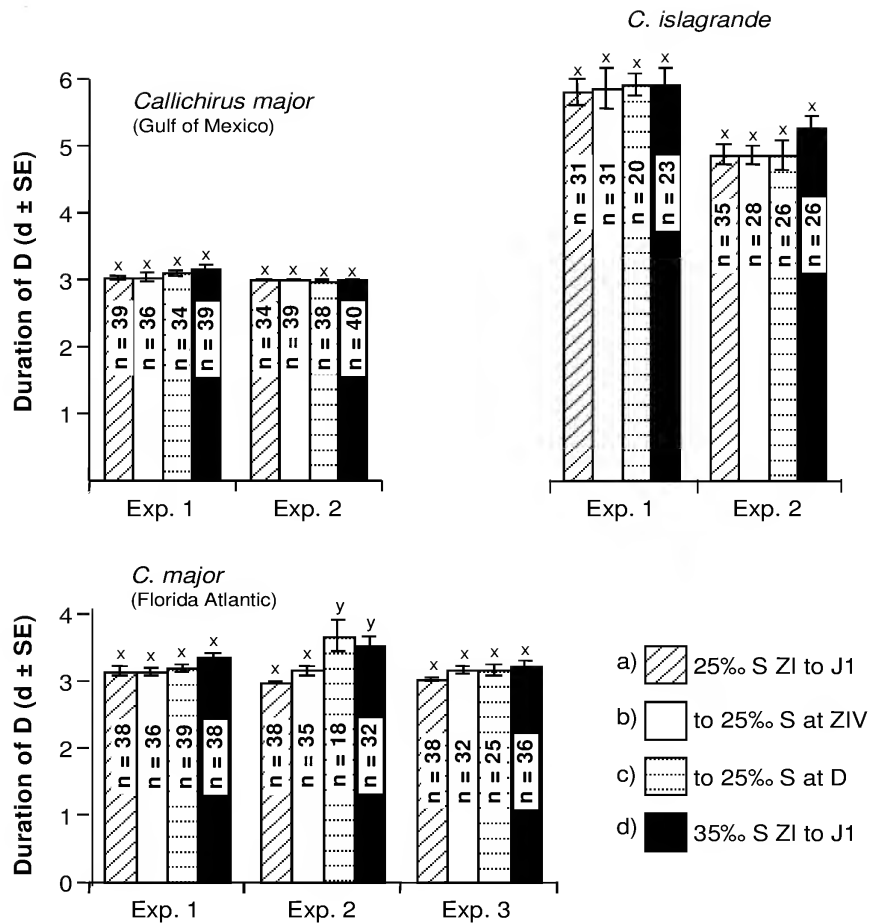
**Figure 3.** Mean duration in days ±SE of D when larval stages were alternatively reared at 25‰ S from ZI to J1 (treatment a), 35‰ S from ZI to ZIII but moved to 25‰ S after the molt to ZIV (treatment b), 35‰ S from ZI to ZIV but moved to 35‰ S after the molt to D (treatment c), or 35‰ S from ZI to J1 (treatment d), lettered treatments corresponding to those in Figure 1. Means with different letters above the error bar differ significantly (*P* = 0.05) within the given experiment for that population with the Tukey-Kramer post hoc test.

animals (92 to 100%) that molted directly from ZIV to D (no ZV) survived metamorphosis to J1, while the percentage that reached J1 among animals which had molted from ZIV to ZV varied from 31 to 83% between treatments (Table 2).

While several larvae of *C. islagrande* also molted to a 5th zoeal stage, the percentage of animals molting directly from ZIV to D (no ZV) was not found to differ significantly between treatments. However, as in the Florida Atlantic population of *C. major*, the presence of ZV did vary between experiments (parental females), and survival to J1 was higher in animals that molted directly from ZIV to D. In both experiments on *C. islagrande*, a few animals molted directly from ZIII to D. A few other larvae were found to be slightly more advanced at the 4th zoeal stage in that they had setae on the pleopods, a character that is usually found at ZV or D (Strasser and Felder, 2000). All of those animals had been maintained at 35‰ S from ZI to ZIII (treatments b, c, d).

**Deformed decapodids**

While there were several deformed decapodids in both *C. islagrande* and the Florida Atlantic population of *C. major*, only one decapodid from both experiments with the Gulf population of *C. major* was deformed. Deformed individuals most commonly had malformed chelipeds or abdomens. However, some individuals suffered from disfigurements of all limbs. In *C. islagrande*, the percentage of deformed decapodids was low in both experiments (<14%) and did not differ significantly between treatments with Fisher's exact-test (Table 3). Experiment 1 with the Florida Atlantic population of *C. major* was similar to experiments run with the Gulf population in that only one decapodid was deformed. In contrast, the percentage of deformed decapodids was high in both Experiments 2 and 3 with the Florida Atlantic population (Table 3). In Experiment 2, the percentage of deformed decapodids was significantly lower in animals maintained at a constant 25‰ S (treat-

**TABLE 2**

Percentage of larvae that molted from ZIV to ZV or directly from ZIV to D for populations of *Callichirus* spp. reared under 4 different salinity (‰) protocols (a-d). Numbered experiments are for separate larval clutches. $n_0$ = number surviving past ZIV; $n_1$ = number molting from ZIV to ZV; $n_2$ = number molting from ZIV to D; %$n_0$ = % surviving past ZIV; %$n_1$ = % of ZV molting to J1; %$n_2$ = % of D molting to J1. Percentages of animals that molted from ZIV to D (no ZV) within each experiment, if followed by different letters (x, y, z), differed significantly ($P < 0.01$) according to results of Fisher's exact-test.

| | Molted from ZIV | ZIV to ZV | | | ZIV to D | | |
| | | | Reached J1 | | | | Reached J1 |
| Experiments | $n_0$ | $n_1$ | %$n_0$ | %$n_1$ | $n_2$ | %$n_0$ | %$n_2$ |
|---|---|---|---|---|---|---|---|
| *Callichirus islagrande* | | | | | | | |
| 1 (a) 25‰ ZI to J1 | 38 | 9 | 24 | 78 | 29 | 76 x | 83 |
| (b) 35‰ ZI to ZIII, 25‰ at ZIV | 37 | 16 | 43 | 75 | 21 | 57 x | 90 |
| (c) 35‰ ZI to ZIV, 25‰ at D | 29 | 9 | 31 | 33 | 20 | 69 x | 80 |
| (d) 35‰ ZI to J1 | 30 | 6 | 20 | 50 | 24 | 80 x | 83 |
| | | | | | | | |
| 2 (a) 25‰ ZI to J1 | 39 | 7 | 18 | 71 | 32 | 82 x | 94 |
| (b) 35‰ ZI to ZIII, 25‰ at ZIV | 28 | 1 | 4 | 0 | 27 | 96 x | 93 |
| (c) 35‰ ZI to ZIV, 25‰ at D | 32 | 0 | | | 32 | 100 x | 81 |
| (d) 35‰ ZI to J1 | 29 | 0 | | | 29 | 100 x | 79 |
| | | | | | | | |
| *C. major* (Gulf of Mexico) | | | | | | | |
| 1 (a) 25‰ ZI to J1 | 39 | 0 | | | 39 | 100 x | 100 |
| (b) 35‰ ZI to ZIII, 25‰ at ZIV | 35 | 0 | | | 35 | 100 x | 97 |
| (c) 35‰ ZI to ZIV, 25‰ at D | 40 | 0 | | | 40 | 100 x | 98 |
| (d) 35‰ ZI to J1 | 37 | 0 | | | 37 | 100 x | 97 |
| | | | | | | | |
| 2 (a) 25‰ ZI to J1 | 35 | 0 | | | 35 | 100 x | 97 |
| (b) 35‰ ZI to ZIII, 25‰ at ZIV | 39 | 0 | | | 39 | 100 x | 100 |
| (c) 35‰ ZI to ZIV, 25‰ at D | 38 | 0 | | | 38 | 100 x | 100 |
| (d) 35‰ ZI to J1 | 40 | 0 | | | 40 | 100 x | 100 |
| | | | | | | | |
| *C. major* (Florida Atlantic) | | | | | | | |
| 1 (a) 25‰ ZI to J1 | 39 | 1 | 3 | 0 | 38 | 97 x | 100 |
| (b) 35‰ ZI to ZIII, 25‰ at ZIV | 37 | 0 | | | 37 | 100 x | 97 |
| (c) 35‰ ZI to ZIV, 25‰ at D | 39 | 0 | | | 39 | 100 x | 100 |
| (d) 35‰ ZI to J1 | 39 | 0 | | | 39 | 100 x | 97 |
| | | | | | | | |
| 2 (a) 25‰ ZI to J1 | 39 | 0 | | | 39 | 100 x | 97 |
| (b) 35‰ ZI to ZIII, 25‰ at ZIV | 39 | 13 | 33 | 69 | 26 | 67 y | 100 |
| (c) 35‰ ZI to ZIV, 25‰ at D | 40 | 32 | 80 | 31 | 8 | 20 z | 100 |
| (d) 35‰ ZI to J1 | 40 | 26 | 65 | 69 | 14 | 35 z | 100 |
| | | | | | | | |
| 3 (a) 25‰ ZI to J1 | 40 | 4 | 10 | 50 | 36 | 90 x | 100 |
| (b) 35‰ ZI to ZIII, 25‰ at ZIV | 39 | 18 | 46 | 61 | 21 | 54 y | 100 |
| (c) 35‰ ZI to ZIV, 25‰ at D | 36 | 23 | 64 | 57 | 13 | 36 y | 92 |
| (d) 35‰ ZI to J1 | 40 | 23 | 58 | 83 | 17 | 42 y | 100 |

## TABLE 3

**Percentage of decapodids found to be deformed for populations of *Callichirus* spp. reared under 4 different salinity (‰) protocols (a-d). Numbered experiments are for separate larval clutches. $n_0$ = number of decapodids; $n_1$ = number deformed among $n_0$; %$n_0$ = % deformed among $n_0$; %$n_1$ = % among $n_1$ (deformed decapodids)that passed through ZV. Percentages of deformed decapodids within each experiment, if followed by different letters (x, y, z), differed significantly ($P < 0.015$) according to results of Fisher's exact-test.**

| | | Deformed decapodids | | |
|---|---|---|---|---|
| Experiment | ($n_0$) | $n_1$ | %$n_0$ | (with ZV) %$n_1$ |
| *Callichirus islagrande* | | | | |
| 1 (a) 25‰ ZI to J1 | 37 | 1 | 3 x | 100 |
|    (b) 35‰ ZI to ZIII, 25‰ at ZIV | 35 | 2 | 6 x | 50 |
|    (c) 35‰ ZI to ZIV, 25‰ at D | 29 | 4 | 14 x | 25 |
|    (d) 35‰ ZI to J1 | 28 | 0 | 0 x | |
| | | | | |
| 2 (a) 25‰ ZI to J1 | 30 | 0 | 0 x | |
|    (b) 35‰ ZI to ZIII, 25‰ at ZIV | 34 | 1 | 3 x | 0 |
|    (c) 35‰ ZI to ZIV, 25‰ at D | 34 | 2 | 6 x | 0 |
|    (d) 35‰ ZI to J1 | 34 | 4 | 12 x | 0 |
| | | | | |
| *C. major* (Florida Atlantic) | | | | |
| 1 (a) 25‰ ZI to J1 | 39 | 1 | 3 x | 100 |
|    (b) 35‰ ZI to ZIII, 25‰ at ZIV | 37 | 0 | 0 x | |
|    (c) 35‰ ZI to ZIV, 25‰ at D | 39 | 0 | 0 x | |
|    (d) 35‰ ZI to J1 | 39 | 0 | 0 x | |
| | | | | |
| 2 (a) 25‰ ZI to J1 | 39 | 0 | 0 x | |
|    (b) 35‰ ZI to ZIII, 25‰ at ZIV | 38 | 9 | 24 y | 100 |
|    (c) 35‰ ZI to ZIV, 25‰ at D | 38 | 25 | 66 z | 100 |
|    (d) 35‰ ZI to J1 | 38 | 23 | 61 z | 100 |
| | | | | |
| 3 (a) 25‰ ZI to J1 | 38 | 1 | 3 x | 100 |
|    (b) 35‰ ZI to ZIII, 25‰ at ZIV | 35 | 8 | 23 y | 100 |
|    (c) 35‰ ZI to ZIV, 25‰ at D | 34 | 11 | 32 y | 100 |
|    (d) 35‰ ZI to J1 | 40 | 9 | 23 y | 100 |

ment a, 0%) than in animals maintained at 35‰ S during the first few stages (treatment b, 24%; treatment c, 66%; treatment d, 61%). Results of Experiment 3 were similar in that animals maintained at 25‰ (treatment a, 3%) had a significantly lower percentage of deformed decapodids than did the other 3 treatments (b, 23%; c, 32%; d, 23%).

### DISCUSSION

In the Gulf population of *C. major*, duration of zoeal stages was significantly shorter in animals maintained at 25‰ S than in animals reared at 35‰ S. Decreased S has been shown to accelerate development of other decapod crustaceans (Vinuesa et al. 1985). This effect was also observed when animals were moved from 35 to 25‰ S at ZIV. The duration of ZIV in animals moved from 35 to 25‰ S at ZIV was similar to that of animals maintained at 25‰ S from hatching. In contrast, the duration of D was not affected by differences in S. This is consistent with previous experiments on this population which demonstrated a decrease in the duration of ZIV with exposure to adult-conditioned water, while the duration of the decapodid stage was unaffected by this stimulus (Strasser and Felder 1998).

As with the Gulf of Mexico population of *C. major*, the duration of the first 3 zoeal stages was shorter in *C. islagrande* when larvae were reared at 25‰ S. However while the duration between molts was longer at 35‰, morphological development was accelerated in some larvae. Several larvae that were maintained at 35‰ S for

the first 3 zoeal stages (treatments b–d) molted directly from ZIII to D, bypassing both ZIV and ZV. Other larvae had setae on the pleopods at ZIV (treatments b–d; 18/96 in Experiment 1, 10/89 in Experiment 2). This is a character that is typically associated with ZV (Strasser and Felder, 2000). None of the larvae reared at 25‰ S molted from ZIII to D or had setae on the pleopods at ZIV.

Unlike in the first 3 zoeal stages, duration of ZIV in *C. islagrande* was longer in animals maintained at 25‰ S than at 35‰ S. However, change in S from 35 to 25‰ at ZIV caused a significant decrease in the duration of this stage. This finding suggests that a change in S may serve as a cue for accelerated development in this species. While both populations of *C. major* were found to accelerate molting from ZIV to D in the presence of sand and adult-conditioned water, *C. islagrande* was unaffected by these stimuli (Strasser and Felder 1998). Duration of D did not differ in animals reared at 35 or 25‰ S. A decrease in S from 35 to 25‰ S at ZIV and D also had no affect on the duration of D.

Durations of the first 3 zoeal stages in the Florida Atlantic population of *C. major* were similar at 25 and 35‰ S. Although duration of ZIII was slightly longer in animals maintained at 35‰ S than it was at 25‰ S, the difference was significant only in Experiment 2. The effect of S on the duration of ZIV was not consistent in that there was no significant effect in Experiments 1 and 2, while the duration of ZIV was significantly shorter at 35‰ S in Experiment 3. The effect of S on the duration of D was also inconsistent. While the duration of D was similar between treatments in Experiments 1 and 3, in Experiment 2 duration of D was significantly shorter in animals reared at 25‰ S or moved from 35 to 25‰ at ZIV than in other treatments.

In previous studies, changes in temperature (Knowlton 1965, Ewald 1969, Sandifer 1973, Scotto 1979), amount or type of food (Templeman 1936, Broad 1957), and S (Robertson 1968, Anger 1991) have been shown to alter the number of developmental stages in various decapods. Whereas presence of a 5th zoeal stage did not appear to be related to S in *C. islagrande*, higher S did increase the incidence of ZV in the Florida Atlantic population of *C. major*. In 2 of 3 experiments with larvae of this population, animals reared at 25‰ S usually molted directly from ZIV to D. Animals reared at 35‰ S were more likely to molt from ZIV to ZV. However, transfer at ZIV from 35 to 25‰ S decreased the chances of molting to ZV. Thus larvae passed through fewer instars in lower S water than in higher for this population in which both adults and larvae appear to live typically

in seawater near 35‰ S. *Scyllarus americanus* (Smith) was also shown to alter the number of instars with changes in S, but this species adds stages when reared at lower salinities (Robertson 1968). *Eriocheir sinensis* was shown to add an extra zoeal stage when reared at a lower S; however only 1 of 5 of these larvae successfully molted to D, which subsequently died before metamorphosis (Anger 1991). None of the larvae from experiments with the Gulf of Mexico population of *C. major* passed through a 5th zoeal stage or were deformed at D. Thus larvae from the 2 populations of *C. major* appear to respond differently to S. Other studies have reported variability in the number of instars between different populations of the same caridean shrimp species (Ewald 1969, Sandifer 1973).

A large percentage of the decapodids were deformed in Experiments 2 and 3 with the Florida Atlantic population of *C. major*. More decapodids were deformed in treatments maintained at 35‰ from ZI to ZIII (treatments b–d) than when maintained at 25‰ S at these stages. The higher incidence of deformity in these treatments appears related to the addition of a larval instar, as all deformed decapodids had passed through a 5th zoeal stage. In previous experiments with this population of *C. major*, the presence of sand and adult-conditioned water at ZIV triggered most animals to molt directly from ZIV to D (no ZV), which led to few deformed decapodids (Strasser and Felder 1999b). In *C. islagrande* the incidence of deformity was low and did not differ significantly among treatments. Unlike the case with Florida Atlantic *C. major*, deformed decapodids were not necessarily restricted to individuals that passed through ZV. Higher salinities also led to deformed decapodids in a population of *Rhithropanopeus harrisii* (Gould) from Portugal (Gonçlaves et al. 1995) and another from North Carolina (Christiansen and Costlow 1975).

Decapodids of *C. sapidus* have been shown to accelerate molting to J1 with a decrease in S at this stage (Forward et al. 1994). Neither *C. major* nor *C. islagrande* accelerated molting from D to J1 in response to a decrease in S, which suggests that decapodids are not responding to decreased S as a cue for settlement. Both *C. islagrande* and the Gulf population of *C. major* accelerated the zoeal phase of development at lower salinities which may contribute to larvae of these animals being retained in nearshore waters. ZIV larvae of both species have been collected in waters near the adult habitat in Louisiana. In general, response of larvae to different salinities was more similar between the Gulf of Mexico populations of 2 different species, than it was between Gulf and Atlantic populations of *C. major*. Thus the adult

habitat seemed to predict the response of larvae to S to a greater extent than did phylogenetic proximity.

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January 2001

# Accurate 3-D Morphological Measurement Using a Structured-Light Range Sensor

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# ACCURATE 3-D MORPHOLOGICAL MEASUREMENT USING A STRUCTURED-LIGHT RANGE SENSOR

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ABSTRACT A single-plane structured light range-sensor was tested to establish its usefulness in acquiring 3-D measurements of fish skulls. Twenty-one distances among 22 landmark points for each of 12 neurocrania of the scorpaenid fish *Neomerinthe hemingway* were taken with digital calipers, with a video-based 2-D imaging system widely used in systematic studies, and with a single-plane structured-light range sensor of inexpensive and simple design. Measures taken by 3-D sensor are highly correlated with those obtained from caliper measurement ($r$ = 0.9995, $P \ll 0.001$), with a precision ranging from 0.08–0.43 mm. Like caliper-based measurements, they are less strongly correlated with measurements derived from projected video-imaging. Most skulls were scanned in just over 3 minutes each. Range maps, typically establishing the (x,y,z) coordinates of more than 75,000 points per scan, can be obtained in about 40–50 CPU seconds using software running on multiple platforms. Sensor data taken from different views can be merged to build a more complete 3-D reconstruction. System design, calibration, and use are discussed. By eliminating error due to perspective effects inherent in measuring from projected video images, such sensors hold considerable promise in quantifying biological shape in 3-D for comparative and functional studies.

> When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge of it is of a meager and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced it to the stage of science.
>
> Sir William Thompson, Lord Kelvin (1824–1907)

## INTRODUCTION

Since measurement of anatomical dimensions provides an extremely important means to distinguish among taxa, it is central to the practice of taxonomy and systematics. Measurement is essential to studies of growth and development, as well as comparative investigations of function. Mensuration also forms a necessary element in the advancement of theoretical systematics by providing empirical data needed to refute hypotheses. Measurable differences, although seldom actually taken, are also implicit in establishing morphological character states for cladistic study and in providing identifications that unify morphological and molecular systematics.

Perhaps because of their ubiquity, much attention has been directed at what measures might be most appropriately taken and how they can be evaluated. Much less attention has been given to the study of how measurements may be acquired more accurately and precisely, with numerous publications often failing to indicate what acquisition methods were used. Given the unification and standardization measurement provides science (Klein 1974, Wise 1994), the constant need to obtain more and better data, and recent advances in computer imaging, it is useful to investigate alternative approaches of measurement.

In taxonomy and systematics, measurements of macroscopic objects have been taken primarily with vernier or dial calipers. In the past, such measurements were transcribed from data sheets and then analyzed. When linked via RS-232 interfaces, electronic calipers now provide a means of acquiring measurement data directly without the need of a separate data entry step. Although this has resulted in data capture rates roughly 5 to 10 times faster than traditional methods, a relatively limited number of measurements can be captured by this means. Consequently, calipers are seldom used to study quantitatively many complex shapes, such as those observed in fish bones. The development of digitizers has permitted morphometricians to use more readily projected images to measure specimens (e.g., Currents et al. 1989, Reilly 1990, Brooks 1991, Hastings 1991), with the use of video-digitizers becoming increasingly common (e.g., Fink 1987, White and Prentice 1988, White et al. 1988, Lindberg 1990, Ray 1990, Sanfilippo and Riedel 1990, Ehlinger 1991, Douglas 1993, Fink 1993, Meacham 1993, McElroy and Kornfield 1993, Newton

and Kendrick 1993, Wimberger 1993, Kaiser et al. 1994, Robinson and Wilson 1995, Zelditch and Fink 1995, Zelditch et al. 1995, McElroy and Douglas 1995). Applications of such 2-D techniques can increase the rate of data acquisition an additional one or 2 orders of magnitude. However, for strongly 3-dimensional objects for which measures can extend out of the plane of the projected image, error resulting from measurement of a foreshortened projected image can be significant. Measurement in multiple orientations and repeated calibration may be required to correct for error due to foreshortening. Although some (e.g., Corner et al. 1992, Richtsmeier et al. 1993) have employed 3-D digitizers to circumvent this problem, most existing tools provide only a limited number of data points for larger objects. Bookstein et al. (1991) successfully demonstrated agreement between measures of the human skull taken from lateral and posteroanterior projections of 3-D cephalograms produced using computed tomography and caliper measures of the same landmarks.

Machine vision offers a variety of sensing methods for accurately and more comprehensively measuring in 3-D. Confocal microscopy provides 3-D measurement for suitably small objects (e.g., Foster et al. 1990, Birkmann and Lundin 1996). Computed Tomography (CT), Nuclear Magnetic Resonance Imaging (NMRI), and Positron Emission Tomography (PET) scanning techniques are powerful, in wide use for medical applications, and have considerable potential for use in measuring biological materials (e.g., Conroy and Vannier 1984, Zangrel and Schultze 1989, Schultze 1991a,b, Kalvin et al. 1995). However, costs associated with these sensors make their use impractical for most systematists. Consequently, development of low-cost imaging systems capable of accurate measurement will likely remain focused on systems utilizing visible light, at least in the near future.

Typically (x,y,z) locations, visible on a target object, are gathered as an array of measured points. This 2-dimensional array of (x,y,z) positions is commonly called a "range map". Range maps may be passively or actively produced. Active methods require special lighting to illuminate the object. Passive methods do not. Without such lighting, range maps are often sparse. Light from a given point on the target may not reach the sensor or it may result in ambiguous values. Nonetheless, one passive method, stereopsis, has seen wide use (Kaufman 1964, Julesz and Miller 1975, Mayhew and Frisby 1976, Yakimovsky and Cunningham 1978, Marr and Poggio 1980, Baker and Binford 1981, Grimson 1981, Mayhew and Frisby 1981, Barnard and Fischler 1982, Marr 1982,

Boyer and Kak 1988). However, stereopsis requires matching points between "left-eye" and "right-eye" images, an ambiguous task without tightly controlled or structured lighting. The resultant range maps can be noisy as well as sparse. Automated steroeopsis thus produces significant measurement error. Manual methods reduce ambiguity, but require much work per measured point. Other passive techniques, such as range-from-focus and shape-from-shading methods (Horn 1975) also provide sparse maps, and they provide relative position only.

Active sensing methods provide more complete range maps. Laser radar probes a target with a collimated beam (e.g., Caulfield et al. 1977, Lewis and Johnston 1977, Nitzan et al. 1977, Riggs et al. 1986). Time of flight is measured for pulsed systems, while FM or AM systems modulate the frequency or amplitude of the transmitted beam and compare the transmitted signal to the return signal to determine distance. However, system cost and complexity are high. Because beams used in such systems dwell on any given point on the target for only a very brief moment, power must be increased to provide sufficient lighting. As a result, such systems are not necessarily eye-safe and are relatively expensive. Flying-dot systems can gather good range data (Rioux 1986, Blais et al. 1988), but again system cost and complexity are high for designs that gather data quickly.

Structured light is a relatively simple active sensing method. Although complex designs involving multiple light stripes (Yeung and Lawrence 1986, Boyer and Kak, 1987) or Gray-coded binary patterns (Inokuchi et al. 1984) are possible, simple sensors that produce range maps of high quality can be built from inexpensive components. A single-plane structured light range sensor is simply a projector, which produces a plane of light, and a camera, which views the intersection of that light plane with the target. The system shown in Figure 1 provides an example of one possible arrangement. When the light plane from the projector intersects a staircased target it forms a light stripe that the camera sees as a series of line segments. With a monochromatic light source and a bandpass filter on the camera, the image contains only those line segments. It is easy to see that the shape of the target defines the general shape of the camera's image. Less obvious, but critical to this sensing method, is that if the optical characteristics of the camera and the geometric relationships of the camera and projector are known, then the (row, column) location of an illuminated point in the image defines a unique (x,y,z) location on the target.

A single-plane structured light sensor is really a 2-D sensor—it gathers 3-D data by assembling a series of 2-D slices. The sensor (or target) is moved so that the light plane sweeps across the volume of interest. Assembling data for individual slices yields a 2-dimensional array of (x,y,z) measures. Each digitized video frame, corresponding to a 2-D slice, yields one column of (x,y,z) values. In our experiments we moved the sensor on an overhead track; moving the target on a stage would yield identical results.

Single-plane structured light range-sensing technology has been widely employed in industrial robotics applications (e.g., Shirai 1972, Agin and Binford 1976, Posdamer and Altschuler 1982, Sato et al. 1982, Yang and Kak 1986, Kak et al. 1987, Wang et al. 1987, Hu and Stockman 1989, Hutchinson et al. 1988, Hutchinson et al. 1989, Hutchinson and Kak 1988, Hutchinson and Kak 1989, Kak et al. 1988, Chen and Kak 1989, Kim and Kak 1991, LaValle and Hutchinson 1991, Cromwell 1992, Cromwell 1993, Wang et al. 1994, Grewe and Kak 1995). However, its use for measuring biological objects has been limited (McLeod 1991).

In this paper, we describe the design, calibration, and use of a 3-D sensor, and the steps involved in processing sensor data for presentation and investigation. We then compare measurements between landmark points on osteological materials using data obtained from the sensor against those gathered using methods already familiar to most systematists. Such comparison provides an estimate of their relative accuracy and a demonstration of their potential usefulness in systematic studies.
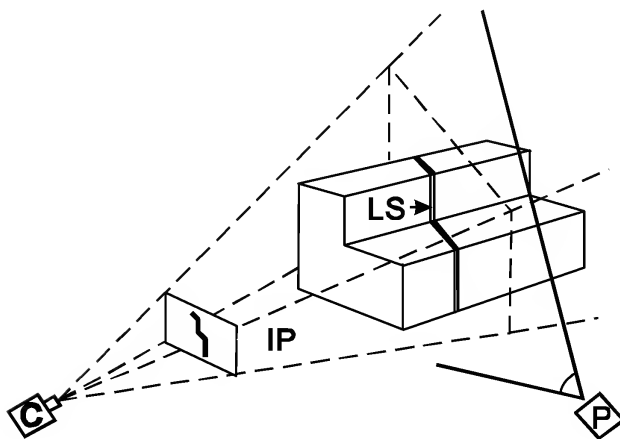


**Figure 1. Range-data gathering with a structured light sensor. C = camera position; P = laser projector; IP = image plane; LS = light stripe.**

## METHODS

Our approach is to scan a target with a low-cost laser range finder to produce a dense array of (x,y,z) measures. A set of images is then displayed on a workstation. As the user selects landmarks of interest, 3-D distances between landmarks are displayed. The overall process may briefly be described as: 1) calibrate the sensor; 2) sweep the sensor across the volume of interest, producing a 2-D array of initial sensor data; 3) convert the sensor data into a 2-D array of (x,y,z) measures; 4) calculate a 2-D array of local surface orientation from the (x,y,z) data; 5) resample the (x,y,z) and local surface orientation arrays to ensure that the displayed images will have appropriate aspect ratios when displayed with square pixels, if necessary; 6) produce images to present the (x,y,z) data in a variety of forms; 7) present those images to the user for specification of landmark points from among the approximately 75,000 to 100,000 measured points; and 8) derive distance measures between landmarks and report these values to the user.

### Sensor Design Considerations

There are 2 primary criteria for designing a structured light range sensor. The first is the field of view. The volume within the camera's field of view beyond the image plane is the "viewing frustum". The intersection of the frustum with the light plane generated by the projector forms a trapezoid. Points within this trapezoid can be simultaneously illuminated and viewed, thereby defining the field of view of the sensor. This imposes a limit on the cross-sectional dimensions of the target object.

The second criterion is resolution, or more appropriately, the spatial quantization. The number of rows and columns in the digitized image limit the possible (x,y,z) measurements to a finite set. The spacing of the corresponding points within the trapezoidal field of view of the range sensor determines the achievable resolution.

Spatial quantization is a function of several variables, including field of view. It is defined in terms of the 3-D distance between points corresponding to adjacent image locations. The 3-D distance between adjacent points on a single row of the image is of particular importance. As illustrated in Figure 2, spatial quantization is a complicated function of the following parameters: 1) the baseline distance, B the perpendicular distance from the light plane to the camera; 2) the toe-in angle, $\Phi$—the angle between the camera's optical axis and the baseline; 3) the horizontal angular field of view of the camera, $\theta_h$—the angle between the left and right

planes of the viewing frustum; 4) the vertical angular field of view of the camera, $\theta_v$—the angle between the top and bottom planes of the viewing frustum; 5) the number of rows in the digitized image, $N_R$; and 6) the number of columns in the digitized image, $N_C$.

Formally, spatial quantization has row and column components:

$$\delta_R(r,c,) = \left| \vec{X}(r,c) - \vec{X}(r+1,c) \right| \qquad (1.1)$$

and

$$\delta_C(r,c,) = \left| \vec{X}(r,c) - \vec{X}(r,c+1) \right| \qquad (1.2)$$

where,

$$\vec{X}(r,c) = \begin{bmatrix} x(r,c) \\ y(r,c) \\ z(r,c) \end{bmatrix} = \begin{bmatrix} B\tan(\Phi + \psi_h(c)) \\ 0 \\ \dfrac{B\cos(\psi_h(c))}{\cos(\Phi + \psi_h(c))}\tan(\psi_v(r)) \end{bmatrix} \qquad (1.3)$$

and where,

$$\psi_h(c) = \tan^{-1}\left[ \left(1 - 2\frac{c-1}{N_C - 1}\right)\tan\left(\frac{\theta_h}{2}\right) \right] \qquad (1.4)$$

$$\psi_v(r) = \tan^{-1}\left[ \left(1 - 2\frac{r-1}{N_R - 1}\right)\tan\left(\frac{\theta_v}{2}\right) \right] \qquad (1.5)$$

A complete derivation of spatial sampling measures, including some sensor design guidelines, is presented in Cromwell (1992). Because $\delta_R(r,c)$ and $\delta_C(r,c)$ can not be readily used to determine the sensor

design parameters (B, $\Phi$, $\theta_h$, $\theta_v$, $N_r$, and $N_c$), sensor design tends to be an iterative process. The best values for these parameters for a particular class of target size and shape are obtained through experimentation.

As for physical construction, Figure 3 depicts a compact sensor design. For this experiment, we used a Pulnix TM-540 camera and a series of lenses, selected and positioned depending on the size and orientation of target skulls. The lens used for each of the scans is given in Table 1. Lateral and dorsal views were taken with the sensor position at location L1 of Figure 3. Ventral views required a top-down orientation (location L2). A wider-angle lens was used for larger targets. The sensor-to-target distances were adjusted so that the target just fit within the field of view. The Pulnix camera has a 510×492 pixel CCD array and produces an RS-170 video signal. This signal was sampled to produce a 512×480 image using an Imaging Technologies FG-100-V video digitizer attached to a Sun 3/280. The light source was a low-cost 0.5 mW HeNe laser producing collimated red light at a wavelength of 632.8 nm.

To spread the collimated beam into a plane we used a 3-element lens system. The beam first passed through a pair of cylindrical lenses separated by 7 mm. The first lens had a focal length of 1.2 mm. The second "lens" was simply a 4 mm glass rod, carefully aligned to present a section free from surface and internal defects. To focus the width of the light stripe to about 0.3–0.5 mm, the beam was passed through a biconvex lens with a focal length of 30 cm separated from the preceding lens by 20 mm.

The sensor can be arbitrarily positioned along a rail. We adjusted the position to view the target from the
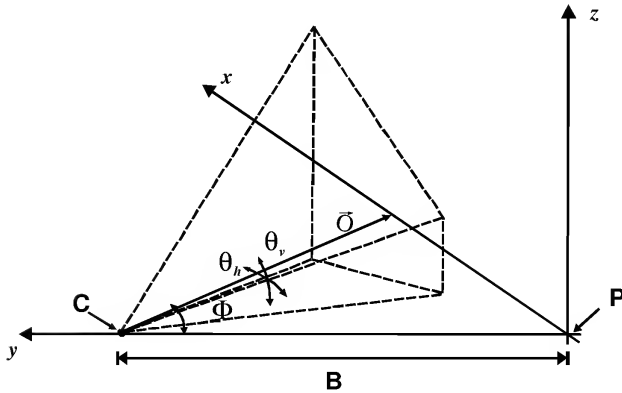


**Figure 2. Geometric relationships among sensor elements that determine the level of spatial quantization for a given sensor design. B = baseline distance, $\Phi$ = toe-in angle, $\theta_h$ = horizontal angular field of view of the camera, $\theta_v$ = vertical angular field of view of camera.**
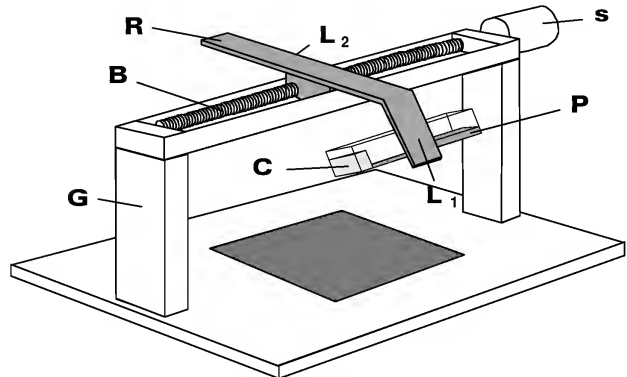


**Figure 3. Sensor design used in this study. B = ball screw carriage; C = camera; G = gantry; $L_1$ = position 1; $L_2$ = position 2; P = projector; R = rail; S = stepper motor.**

14

## TABLE 1

**Spatial Sampling Granularity For All Datasets [2] Camera views (dorsal, lateral, and ventral) are indicated in parentheses by D, L, and V respectively, with the camera position (position 1—toward end of arm, position 2—directly overhead) as specified in Figure 3.**

| Dataset Name | Spatial Quantization, mm | | Typical Lens |
| --- | --- | --- | --- |
| | Minimum | Maximum | |
| GCRL 26643 (D1)0.2115 | 0.6479 | 0.3379 | 75mm@f/5.6 |
| GCRL 26666 (D1)0.1661 | 0.2579 | 0.2038 | 75mm@f/8 |
| GCRL 26668 (D1)0.0655 | 0.1006 | 0.0799 | 75mm@f/8 |
| GCRL 26669 (D1)0.2326 | 0.6212 | 0.3539 | 75mm@f/5.6 |
| GCRL 26670 (D1)0.1526 | 0.2769 | 0.1997 | 75mm@f/8 |
| GCRL 26671 (D1)0.1471 | 0.2789 | 0.1963 | 75mm@f/8 |
| GCRL 26672 (D1)0.1400 | 0.2954 | 0.1946 | 75mm@f/8 |
| GCRL 26674 (D1)0.2068 | 0.6662 | 0.3356 | 75mm@f/5.6 |
| GCRL 26676 (D1)0.1432 | 0.2940 | 0.1967 | 75mm@f/8 |
| GCRL 26677 (D1)0.2021 | 0.6709 | 0.3307 | 75mm@f/5.6 |
| GCRL 26678 (D1)0.1269 | 0.2102 | 0.1602 | 75mm@f/8 |
| GCRL 26689 (D1)0.1772 | 0.7227 | 0.3105 | 75mm@f/5.6 |
| GCRL 26643 (L1)0.1605 | 0.2650 | 0.2025 | 75mm@f/8 |
| GCRL 26666 (L1)0.1524 | 0.2727 | 0.1986 | 75mm@f/8 |
| GCRL 26668 (L1)0.0677 | 0.0968 | 0.0800 | 75mm@f/8 |
| GCRL 26669 (L1)0.1546 | 0.2742 | 0.2010 | 75mm@f/8 |
| GCRL 26670 (L1)0.1374 | 0.2960 | 0.1929 | 75mm@f/8 |
| GCRL 26671 (L1)0.1342 | 0.2994 | 0.1909 | 75mm@f/8 |
| GCRL 26672 (L1)0.1580 | 0.2641 | 0.2001 | 75mm@f/8 |
| GCRL 26674 (L1)0.1595 | 0.2690 | 0.2030 | 75mm@f/8 |
| GCRL 26676 (L1)0.1466 | 0.2812 | 0.1965 | 75mm@f/8 |
| GCRL 26677 (L1)0.1602 | 0.2987 | 0.2122 | 75mm@f/8 |
| GCRL 26678 (L1)0.1456 | 0.2095 | 0.1728 | 75mm@f/8 |
| GCRL 26689 (L1)0.1432 | 0.3391 | 0.2081 | 75mm@f/8 |
| GCRL 26643 (V2)0.1786 | 1.9185 | 0.4154 | 25mm@f/4 |
| GCRL 26666 (V2)0.1171 | 0.4121 | 0.1970 | 75mm@f/8 |
| GCRL 26668 (V2)0.0962 | 0.1786 | 0.1278 | 75mm@f/8 |
| GCRL 26669 (V2)0.1644 | 3.2031 | 0.4286 | 25mm@f/4 |
| GCRL 26670 (V2)0.1471 | 0.3079 | 0.2047 | 75mm@f/8 |
| GCRL 26671 (V2)0.1452 | 0.2976 | 0.2006 | 75mm@f/8 |
| GCRL 26672 (V2)0.1535 | 0.2879 | 0.2049 | 75mm@f/8 |
| GCRL 26674 (V2)0.1786 | 1.9443 | 0.4161 | 25mm@f/4 |
| GCRL 26676 (V2)0.1432 | 0.3171 | 0.2045 | 75mm@f/8 |
| GCRL 26677 (V)0.2094 | 0.9245 | 0.3781 | 25mm@f/4 |
| GCRL 26678 (V2)0.1364 | 0.3390 | 0.2035 | 75mm@f/8 |
| GCRL 26689 (V2)0.1953 | 1.1991 | 0.3943 | 25mm@f/4 |

desired direction and to attain an adequate field of view. The rail was mounted to a ball-screw carriage, with the long axis of the rail perpendicular to the carriage's direction of travel. The ball screw was mounted above the work table, and was driven by a stepper motor that received drive signals from a serial port of the Sun 3/280.

**Data Gathering**

Operation is quite simple and takes under 4 minutes per scan. The video digitizer grabs a 512×480 frame, the computer processes the resulting image to extract (row, column) positions of illuminated points, and the stepper motor moves the sensor. Movement (translation) is perpendicular to the projected light plane, and the distance
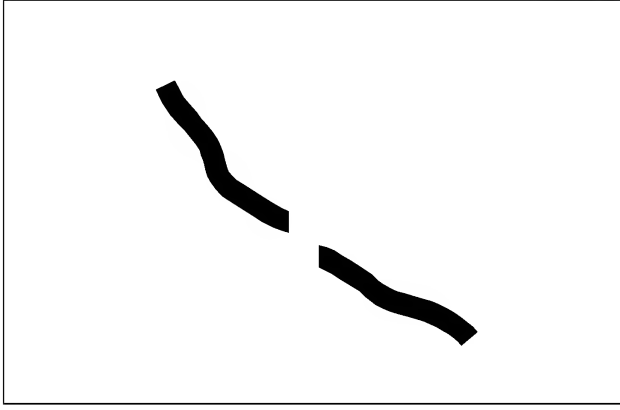
**Figure 4. Arbitrary single image of light stripe.**

moved per step is the total target length divided by the number of slices. This continues until the desired number of slices have been digitized. Each slice contributes a 480-point column of data to the range map.

For processing a single image, consider the sensor image in of an arbitrary "slice" in Figure 4. Due to orientation of the camera relative to the light plane, the light stripe will be roughly perpendicular to the scan lines in the image. Some rows may have no illuminated points. We describe the shape of the illuminated stripe segment(s) in a frame by a series of numbers, one per row, where zero indicates that no point in that row was illuminated and any number other than zero indicates the column location of the illuminated point. For a 512×480 image, this generates a sequence of 480 numbers in the range 0 through 512 inclusive. In the terminology of machine vision, this is frequently called "offset data", as it expresses the offset of the light stripe from the left margin of the image.

Offset data is stored in a 2-D array. Each column of the array represents a slice derived from one digitized video frame. The row position within a column is the row position from the associated frame. The value stored at offset [i,j] is thus the offset data from the j'th row of the i'th frame. If zero is stored, the point is invalid—there was no measurement made for row j of frame i. If a non-zero offset distance d is stored, then a 3-D position was measured. It has been stored in terms of an image-plane (row, column) position equal to (j,d).

The data structure just described assumes an ideal image. An actual video image will present a somewhat fuzzy stripe, more than one pixel wide, against a background that is not entirely dark. To deal with real images, we have achieved acceptable results with the following procedure. As shown diagrammatically in Figure 5A, for each scan line we find the brightest pixel. If that pixel is not above some absolute threshold, $T_A$ (which may depend on light source, lens speed, and stand-off distance), then store zero. If that pixel is at least as bright as $T_A$, then we test pixels at an outlier distance w on either side of the peak. If they are not dimmer than $T_R$, a percentage of the intensity of the brightest pixel, store zero. As shown in Figure 5B, this avoids artifacts caused where the light plane grazes a nearly coincident surface, keeping only isolated peaks.

To reduce fuzziness caused by vibration, which may result from using long focal length lenses positioned toward the end of the rail, short time delays were added between frames during sensor movement. To limit noise introduced by low light performance of the Pulnix camera, we averaged 4 digitized frames for each slice when using long focal length lenses.
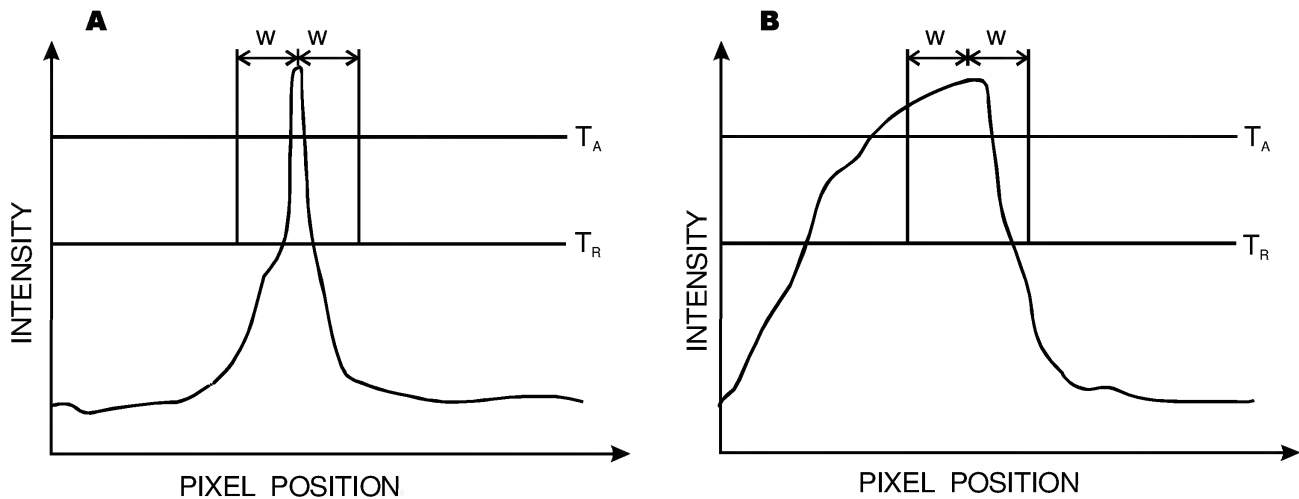


**Figure 5. Measured Intensity Values Across Light Stripe. A = Valid peak; $T_A$ = absolute threshold; $T_R$ = relative threshold; W = outlier distance; B = Invalid peak resulting from grazing.**

16

The distance to these outlier pixels and the absolute threshold of the brightest pixel are specific to a particular sensor design. For the sensor used in these experiments, with pixels digitized to take intensity values from zero through 255, we used an absolute threshold of 20, a relative threshold of 0.66 times the peak intensity, and an outlier distance of 10 pixels. If the pixel in question meets the criteria associated with the absolute and relative thresholds, then its column position is stored in the offset data. We also save the intensity of the original point. This means that we have intensity data that is registered to (x,y,z) location—the utility of this is explained in a later section. The intensity is stored in the same order as the offset data. While the offset data encodes (x,y,z) in a somewhat indirect way, it is possible to plot the offset data to produce a composite light-stripe image (Figure 6). This image strongly suggests the 3-D shape of the surface. It provides immediate feedback to the user regarding the quality of the measurements.

We store both offset and intensity as ASCII values, for maximum portability. The data are run-length-encoded, so that stretches of missing data are replaced by their lengths. The file has a header that includes the calibration matrix, sensor use characteristics, date of capture, the name of the user, and a user-specified comment field, which allows us to record information about the specimen. Our comment field included the catalog number of the specimen and other relevant information about the scan.

## Calibration

The sensor records provides only (row, column) information. Measurement requires (x,y,z) locations. Sensor calibration provides a mapping from image plane coordinates—(row, column), or (r,c)—into world coordinates—(x,y,z). It might seem appropriate to calibrate the sensor by trigonometric analysis, as done in equation 1.3 to define $\bar{X}(r,c)$. However, this is not the case, as the optical and geometric characteristics are difficult to measure and small errors have profound effects. The best method is to solve analytically for a calibration matrix, using known (x,y,z) and (r,c) pairs. In other words, image a calibration target with features in known (x,y,z) positions, measure the resulting (r,c) image locations, and solve for the relationship providing the mapping from image coordinates (r,c) to world coordinates (x,y,z).

Our calibration target was a small panel with 6 pins protruding from known locations. We use the calibration method described in Chen and Kak (1987) to map the image plane onto the light plane. This yields a calibration matrix $T$, where:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} \dfrac{a}{d} \\ \dfrac{b}{d} \\ \dfrac{c}{d} \end{bmatrix} \quad \text{where} \quad \begin{bmatrix} a \\ b \\ c \\ d \end{bmatrix} = T \begin{bmatrix} r \\ c \\ 1 \end{bmatrix} \qquad (2.1)$$
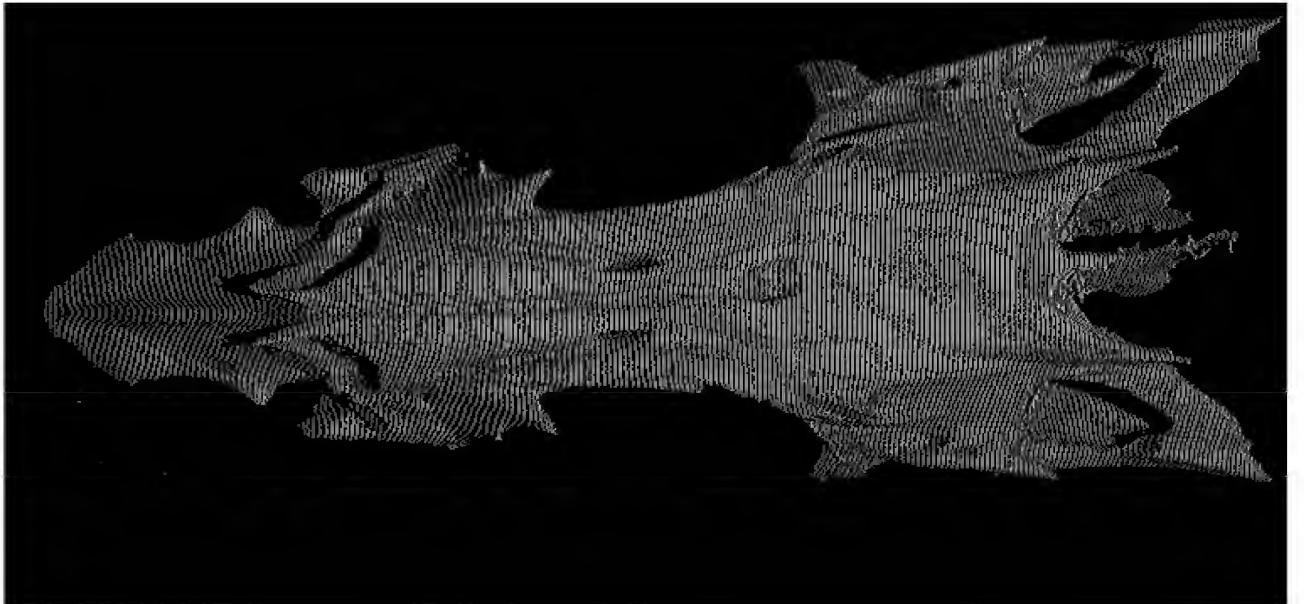


**Figure 6. Unrectified, composite light-stripe image (GCRL 26643 in dorsal view).**

or:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} \dfrac{T_{11}r + T_{12}c + T_{13}}{T_{41}r + T_{42}c + T_{43}} \\[2ex] \dfrac{T_{21}r + T_{22}c + T_{23}}{T_{41}r + T_{42}c + T_{43}} \\[2ex] \dfrac{T_{31}r + T_{32}c + T_{33}}{T_{41}r + T_{42}c + T_{43}} \end{bmatrix} \qquad (2.2)$$

Each pair of image and world coordinates yields 3 equations in twelve unknowns, the elements of T. A set of 4 calibration points would be adequate to solve for T. Our problem is overdetermined, so we form the normal equations as described in Chen and Kak (1987), and find the linear least-squares solution as described in sections 2.0–2.1 of Press et al. (1988).

Given T, we would like to calculate bounds on its spatial quantization. The finest and coarsest sampling will both occur along the margins of the image, as long as the image does not include the point on the light plane that is closest to the camera. The error to consider is a one-pixel error in column position for a given row, as that is the error associated with incorrectly choosing the peak in a row of the image. So, for each border pixel, we calculate the 3-D distance between the (x,y,z) coordinates corresponding to that pixel and its neighbor to the left or right. A typical error is that same measure carried out for a pixel in the region of the frame where illuminated points typically appear. The calculation of this error is critical, as error in peak detection and selection is the source of practically all error in establishing (x,y,z). Sub-pixel peak detection and selection provides a means of improving spatial quantization. We recalibrated the sensor before every scan of every target to minimize error. The typical and bounding spatial sampling values for all datasets are shown in Table 1. Note that these values provide the bounds on the best possible accuracy for a given configuration. Typical best-case calibration errors, e(T), were in the range 0.05–0.2 mm. If e(T) is within or below the spatial quantization (as it always was in this study), that provides high confidence in the accuracy of the calibration matrix T.

Applying the calibration matrix to the offset data yields a range map $\vec{X}$, a 2-D array of 3-D vectors. $\vec{X}[i,j]$ is the vector (x,y,z) stored in column i, row j of this array. This corresponds to the (x,y,z) position obtained from the j'th row of the i'th digitized frame. We then add in the slice-to-slice translations. We translate the sensor along the y-axis, as the projected light defines the x-z

plane. The translation per step is just enough to cover the long dimension of the target in 256 slices. If each step is $s$ millimeters, then every (x,y,z) vector stored in column i has $(0, s \cdot i, 0)$ added to it. In other words, for every i in the range [0,256] and each j in [0,480], if point [i,j] was valid, we make the assignment:

$$\vec{X}[i, j] = \vec{X}[i, j] + \begin{bmatrix} 0 \\ s \cdot i \\ 0 \end{bmatrix} \qquad (2.3)$$

By "valid", recall that we mean those points for which we extract an offset value and thus are able to calculate (x,y,z). This is typically about 50–70% of the points per scan.

**Self-Occlusion**

The only measurable points are those that can be simultaneously illuminated with the laser and viewed with the camera. If the light source and detector were coincident, as is the case with laser radar, there would be no missing data. Of course, for such a sensor the light stripe would be a straight line in every image and thus reveal no 3-D information.

With the camera outside the light plane, as it must be, there is a set of points that can be viewed but not illuminated, and a set that can be illuminated but not viewed. This is what is referred to as self-occlusion. Consider a smooth spherical target. Almost 50% of the surface can be viewed, and almost 50% can be illuminated, but the overlap is perhaps only 30–40% of the total surface area. If the target has protruding structures, those structures may cast 2 "shadows". One shadowed region is the set of points that cannot be illuminated because an occluding structure blocks the light plane. These illumination-occluded points will lie in the same slice, thus the same range map column, as the occluding surfaces. The other shadowed region is the set of points that cannot be viewed because an occluding structure blocks the camera's line of sight. These view-occluded points will not necessarily lie in the same slice, but for a "left-eyed" sensor configuration like ours, with sensor translation to the right, they appear to the right of the occluding structure in the range map. Many points near an occluding structure will belong to both occlusion sets.

**Processing the Range Map**

The above section describes how offset data can be captured and converted to a 2-D array of (x,y,z) vectors.

The next step is the calculation of the local surface normals. A detailed description of the calculation of surface normals and local curvatures from a range map is given by Yang and Kak (1986). Simply stated, $\vec{X}_u$ and $\vec{X}_v$ are 2-dimensional arrays of 3-D vectors, just as $\vec{X}$ is a 2-dimensional array of (x,y,z) locations. $\vec{X}_u[i,j]$ and $\vec{X}_v[i,j]$ are the partial derivatives of the range map $\vec{X}$ with respect to row and column position, respectively and where "*" implies convolution:

$$\vec{X}_u = \vec{X} * \begin{bmatrix} \dfrac{-1}{12} & \dfrac{-4}{12} & \dfrac{-1}{12} \\ 0 & 0 & 0 \\ \dfrac{1}{12} & \dfrac{4}{12} & \dfrac{1}{12} \end{bmatrix} \quad (2.4)$$

$$\vec{X}_v = \vec{X} * \begin{bmatrix} \dfrac{-1}{12} & 0 & \dfrac{-1}{12} \\ \dfrac{-4}{12} & 0 & \dfrac{4}{12} \\ \dfrac{1}{12} & 0 & \dfrac{1}{12} \end{bmatrix} \quad (2.5)$$

The surface normal vector at the location [i,j] is thus:

$$\vec{S}[i,j] = \frac{\vec{X}_u[i,j] \times \vec{X}_v[i,j]}{\left| \vec{X}_u[i,j] \times \vec{X}_v[i,j] \right|} \quad (2.6)$$

where, $\times$ is the cross product operator.

This means that $\vec{s}$ would be defined only at points that have 8 valid neighbors. If a point is valid, but lacks a completely valid neighborhood, the surface normals are examined at its 8 neighbors. If a surface normal could be calculated at one or more neighbors, then a neighboring surface normal vector is assigned. If there is a choice of more than one neighboring surface normal vector, then we select the one for which the point in question best fits the plane of the corresponding 3×3 neighborhood.

**Image Rectification**

If we simply display the range map, coding intensity or hue for 3-D vectors (as discussed in detail below), then depending on the sensor field of view and the sensor translation per slice, we may or may not have an image that appears correct when displayed with square pixels. The (x,y,z) vectors will be correct, but the row and column dimensions of the image may be such that it has the appearance of being compressed or stretched. This can be corrected by resampling the range map through a step we refer to as "rectification".

The range map is first transformed so that the average surface normal vector points in the direction (0,0,1). Since the range map is filled with one column per measured slice, points lying along one column are at a constant value of x. Therefore, the derivative dx/di describes the step per slice, and dx/dj is zero (where i,j are indices within the range map corresponding to the ith row in the jth original frame). After the transformation, dy/di is essentially zero, dy/dj is essentially some
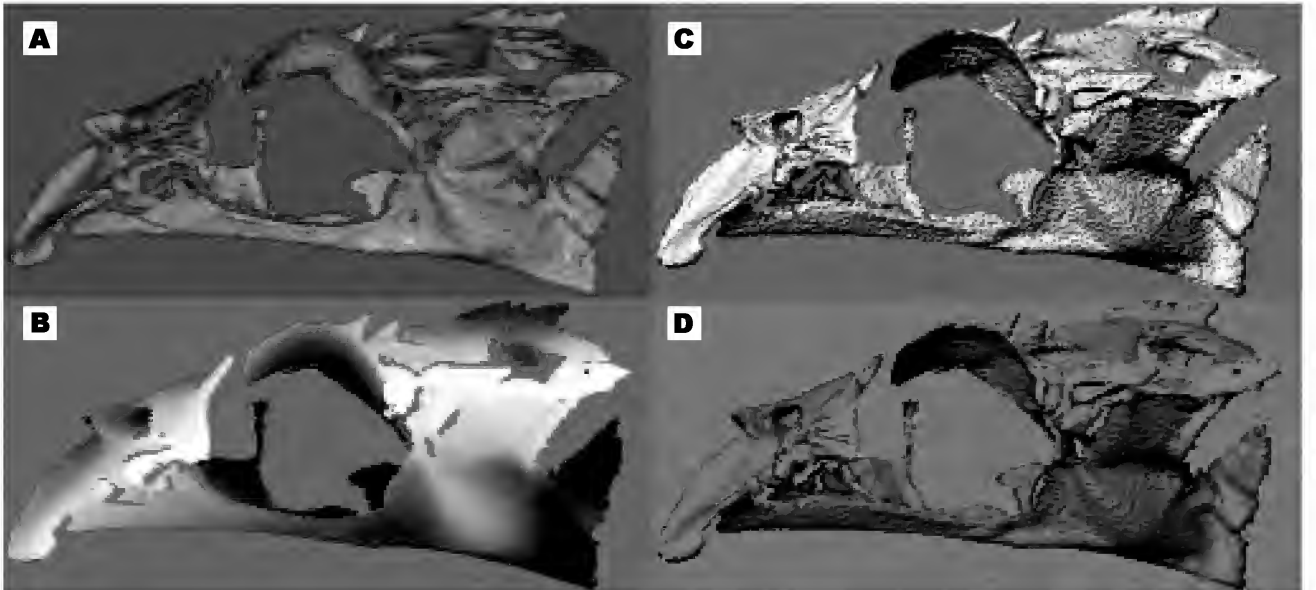


**Figure 7. Reconstruction of Measured Target. A = Registered intensity data; B = Z-value coded as intensity; C = Rendered image D = Encoding of position and orientation.**

non-zero constant, and both dz/di and dz/dj vary with the 3-D shape of the measured surfaces. We resample the range map to make dx/dj and dy/di roughly equal, which ensures that images displayed with square pixels present the expected aspect ratio. The surface normal map is then recalculated for the resampled $\bar{X}$.

## Presentation and Visualization

Given a range map and a map of surface normal vectors, we can produce a rendered image. This rendered image displays the intensities we would expect if the 3-D surface were lit by a point light source, ignoring shadow effects. Given a location of a point on a surface, the expected intensity is a function of the angles between 3 vectors: 1) the local surface normal vector, 2) the vector to the hypothesized viewpoint, and 3) the vector to the hypothesized light source. The precise function used is defined by the lighting model (see Foley and van Damm 1984, Ballard and Brown 1982, Marr 1982 for specific algorithms). We used a combination of Marr and Minnaert lighting models, positioning the light source location to illuminate the surface from above our left shoulder. Note that this is rendering only, not raytracing, which is far more computationally expensive. Rendering alone presents adequately realistic imagery for landmark selection.

We now produce 4 images. The first, (Figure 7A) is the registered intensity data, and it resembles a photograph of the target. The second (Figure 7B) encodes z as intensity. The third (Figure 7C) is the rendered image. The fourth (Figure 7D) encodes both position and orientation. We can use hue on a computer monitor to encode z, with blue furthest from the sensor and red closest (Cromwell, 1997). The intensity is that of the rendered image. The combination of these 4 images guarantees that any measured feature will be visible in at least one of them. Suture lines, for instance, are too small to show up in the range map but they frequently appear in the registered intensity image. Many uniform regions within the intensity image have complex 3-D shapes revealed by other images.

## Data Extraction

The above steps produce a 2×2 panel of 4 images. This panel is displayed on a workstation screen, and the user selects points. We have developed a simple interface in the X Window System\(™ that allows the user to accurately select points for measurement using a mouse. The corresponding (x,y,z) location follows immediately from the [i,j] index of the selected image point. The user

can extract positions and orientations of single points, distances between selected points, or cross sections along arbitrary cutting planes. The selection can be done on any of the 4 images presented, so a pair of points does not have to be visible in a single image.

## Registration, Range-map Merging, and Raytracing

Thus far, we have limited discussion to a single translational scan of the target. In addition to the small regions of self-occlusion described earlier, this sensing mode restricts the range map to less than 50% of the target. An obvious next step is to integrate range maps gathered from a variety of directions to fully image the object in 3-D. To do this we must solve several problems.

First consider the problem of merging 2 range maps taken from views perhaps 90° apart. Let us refer to these range maps as $\bar{X}_1$ and $\bar{X}_2$. We have thus far used rows and columns of such range maps to define an appropriate grid for presentation. In merging range maps it is convenient to use the points as vertices in a mesh, representing the surface as one or more contiguous regions of triangular facets that tessellate the surface. If the target were roughly spherical, we would expect about half of each range map to cover a common area. Thus, half of $\bar{X}_1$ would form a mesh roughly coincident with the mesh formed by $\bar{X}_2$. We say "roughly coincident" because spatial quantization and measurement error will prevent exact coincidence. Even in the absence of measurement error, $\bar{X}_1$ and $\bar{X}_2$ will, in all probability, sample the 3-D spaces slightly differently with individual points not falling exactly at the same locations.

Consider the union of these range maps, which forms a more complete model of the object and can be expressed as,

$$\vec{X}_u = \vec{X}_1 \cup \vec{X}_2 \qquad (2.7)$$

with $\bar{X}_1$ and $\bar{X}_2$ transformed so that their coordinate frames are coincident. $\bar{X}_u$ could be formed in 3 ways: 1) by moving the target mechanically between scans, with sufficient precision to provide the reverse translation; 2) by a human expert picking landmarks visible in both range maps to derive the needed transformation; 3) by a procedure in which corresponding landmarks in the 2 range maps are identified automatically, without human intervention. Presently, only the first 2 approaches are practical and we have used both. After the union, $\bar{X}_u$ now describes roughly 75% of the object. However, approximately one-half of $\bar{X}_u$ is redundant.

A second major problem is that we can no longer display the range map using the indices as a grid. Instead, we must resort to raytracing to create a realistic image. Since our measured points are described by several sets of points gathered from rectangularly sampled grids, for each range map we form a triangular mesh. We thus have a (rather long) list of triangular facets described by the (x,y,z) positions of their vertices. To perform raytracing we follow techniques described in detail by Glassner (1989). For each pixel in the image, raytracing determines which, if any, facet will appear and how it will be rendered. If the 2 range maps are of high quality and if the registration between the maps is accurate, the region they share will appear as a finely-mixed combination of the 2 meshes. However, it is possible for many facets of one range map to be completely obscured by facets of the other. In such cases, there may be facets that are completely inside the surface, so that they would not appear from any exterior viewpoint. Although it would be difficult to establish a list of such facets analytically, it would be relatively easy to generate a number of raytraced views from canonical positions and then search the union range map for facets that appear in none of these views. Figure 8 shows the results of multi-scan registration and merging using 3 views (dorsal, lateral, and ventral).

For many applications it may be reasonable to delete such facets from later consideration, given the computational expense of raytracing. If they were visible only from very limited regions of space, their deletion would have little effect on overall accuracy or completeness. Nonetheless, more work needs to be done to facilitate landmark selection and measurement from raytraced imagery.

**Computer Hardware Used**

As previously mentioned, a Sun 3/280 was used to drive the scanner and digitize the images. The sensor used was a general-purpose machine vision tool, and was not specially designed for biological applications. In fact, it was designed for far coarser sampling of larger targets. The use of the Sun was due to the arrangement of available hardware rather than to any specialization. Since then, we have implemented the system on a PC platform running the Linux operating system. Readers interested in constructing such a system may contact the senior author.

Data analysis, from offset data to presentation images, was done on both Sun (4/390S and Sparc 1000) and PC (K6-333 MHz CPU, 32 MB RAM) platforms. On both Sparc platforms, a 256×480 range map can be processed and presented in 40 to 50 CPU seconds. On the PC platform, range map processing and presentation takes only 10 CPU seconds.
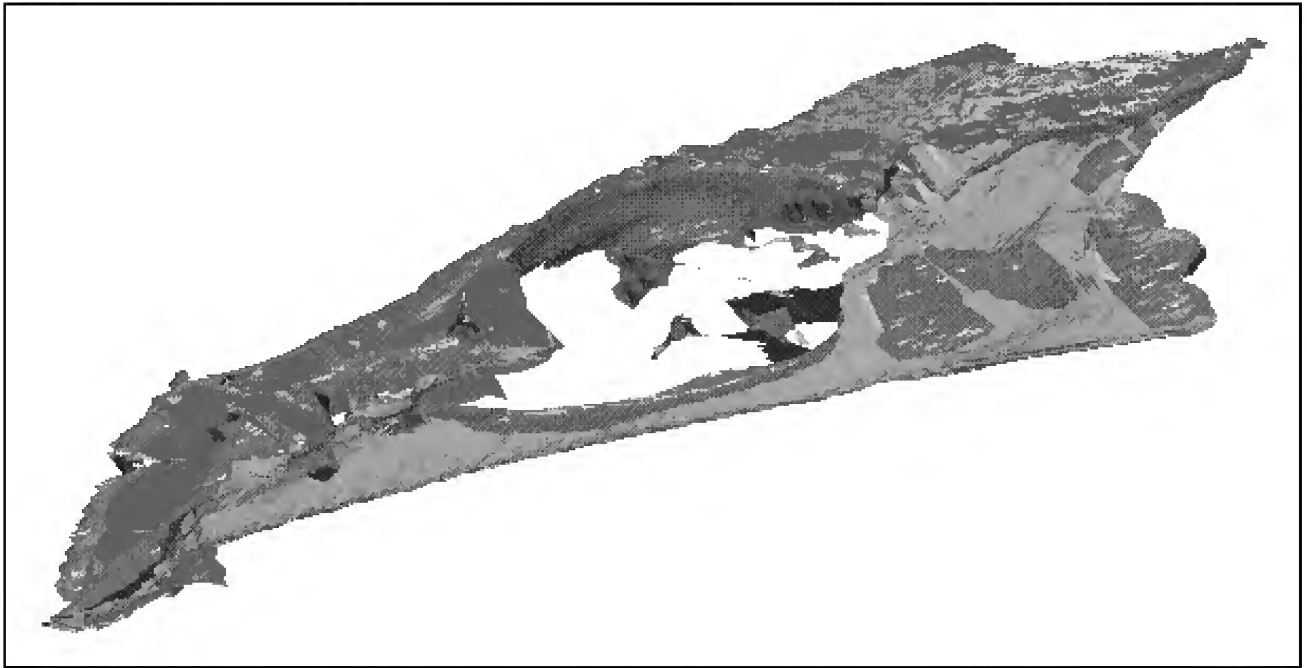


**Figure 8. Composite reconstruction produced through the union of 3 "canonical" views (dorsal, lateral, and ventral) of GCRL 26666. Note the reduction in self-occlusion as compared to Figure 7.**
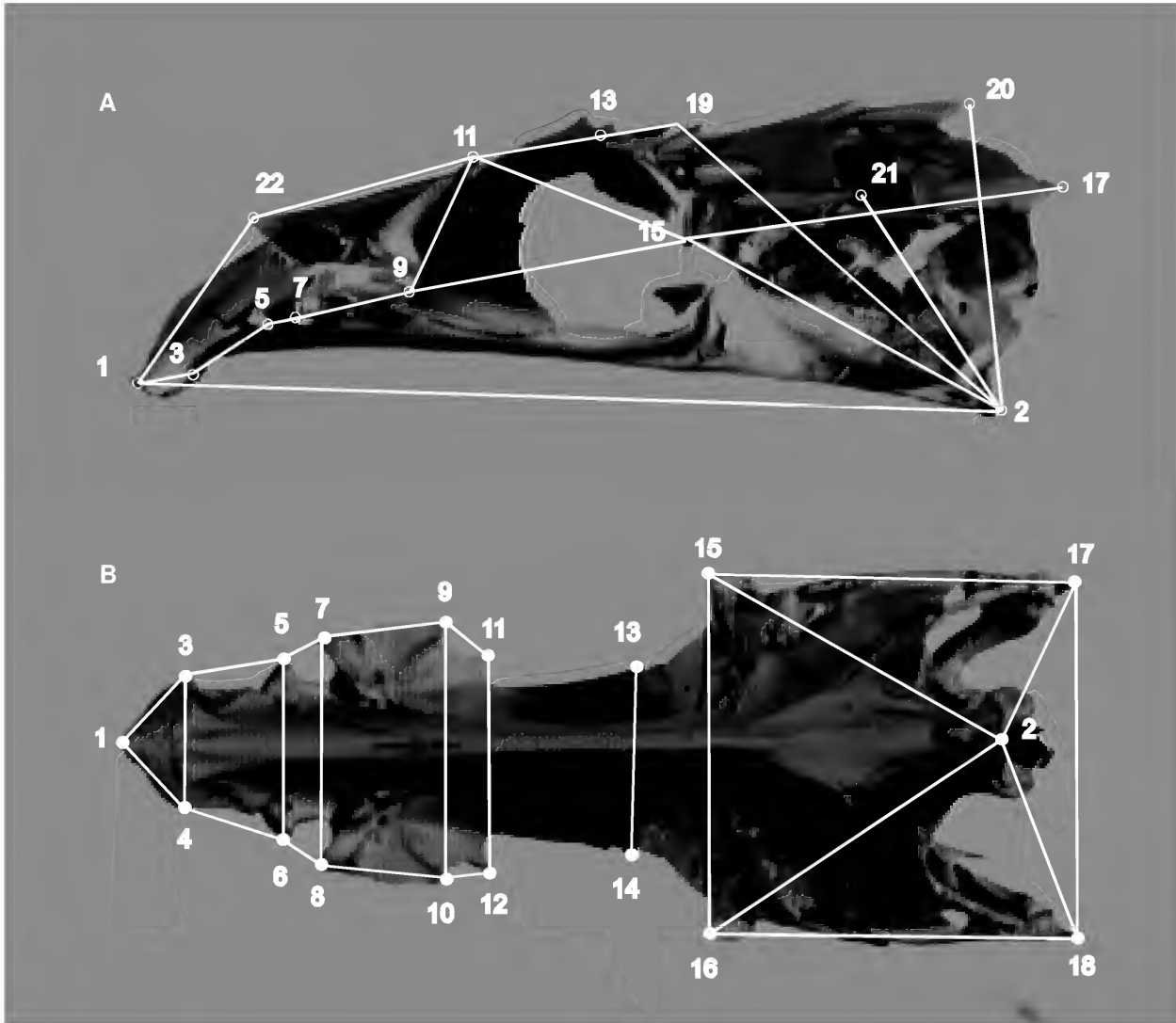
Figure 9. Selected landmark points and distances (in white) used to compare sensor-derived measures with those taken using caliper and projected-video imaging. A = Lateral view; B = Ventral view. 1) anteriormost median tip of median ethmoid, 2) posteriormost ventral margin of basioccipital, 3) lateralmost extension of median ethmoid on left side [4 on right side], 5) lateralmost point on lateral extension lateral ethmoid immediately anterior to palatine socket, [6 on right], latero-anterior most point on lateral extension of lateral ethmoid immediately posterior to palatine socket [8 on right side], 9) lateralmost point of ventroposterior margin of lateral ethmoid at anterior rim of orbit [10 on right side], 11) tip of left preorbital spine [12 on right side], 13) tip of supraorbital spine [14 on right side], 15) anterolateral tip of left dermosphenotic [16 on right side], 17) posteriormost tip of left postemporal spine [18 on right side], 19) tip of left posttemporal spine, 20) tip of left nuchal spine, 21) tip of left pterotic spine, 22) tip of anteriorprojection of left frontal. Landmark points 19–2 not consistently visible or damaged in some specimens and not used in computations shown in Figure 10.

## Specimen Preparation and Caliper and 2-D Measurement

Specimens of the scorpaenid fish *Neomerinthe hemingway* were taken near the mouth of the Mississippi River and frozen for subsequent skeletonization. Catalog numbers for these specimens are provided in Table 1. This species was selected because of its relatively large size and availability. Partially frozen specimens were autoclaved for 6 to 12 minutes at 123°C, depending on size, to facilitate removal of muscle and other tissues without disarticulating the skulls. Posttemporal bones of some specimens were subsequently reattached. To minimize reflections that can result in beam deflection and image loss and to insure that adequate light is more uniformly returned off more translucent regions, all skulls were spray painted with a flat white enamel prior to measurement of any kind.
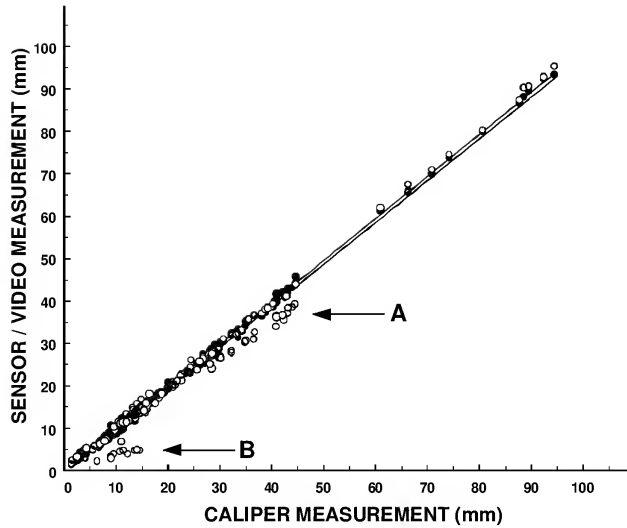
22

and $P \ll 0.001$ (Figure 10).The corresponding correlation for inter-landmark distances measured by sensor and projected video-imaging is somewhat lower ($r = 0.9934$ and varies depending primarily upon the orientation used for a given measurement). Four measures that, when taken in ventral view exhibit notable foreshortening are primarily responsible for the difference between projected video-based measurement and either caliper and sensor based methods (distance between points 2 and 15, 2–16, 9–11 and 10–12). The first 2 distances are relatively distant, but extend simultaneously from the broadest dorso-lateral part of the skull (dermosphenotic) to the postero-ventral margin of the medial skull axis (basisphenoid). The second pair of measurements (posterior margin of lateral ethmoid process to tip of preocular spine) appear proximate in ventral view, but extend strongly dorso-ventrally, when viewed laterally.

## Discusson

Although our system was not specifically designed to measure biological objects, our results indicate it produces abundant data within the range commonly used in comparative morphometrics. Data storage costs increase roughly linearly with an increase in the number of pixels measured. However, this is not prohibitive as compression can result in considerable savings. Our offset data files ranged from 69–158KB compressed and about 3.2 MB uncompressed. Processing time is also roughly linearly related to the number of points in the range map. Increases in the number of optical slices per scan, as well as increases in pixel density per digitized video frame, could be accommodated without exorbitant computational expense. For a system costing only about $2,000, excluding the workstation and labor costs, we believe our results demonstrate the practicality of single-plane structured light measurement of osteological materials.

At sharp edges, finite beam width and optical bloom limit achievable accuracy. We have coated our targets with a matted surface, carefully selected camera optics, and used appropriate lens speed to minimize ambiguity and loss of resolution. For this reason, we limited our inquiry to relatively large, non-specular objects that are relatively hard, opaque, and dry. Nonetheless, significant scope for improvement at relatively low cost exists and additional experimentation will likely improve accuracy and the range of objects that may be examined. Since these experiments were conducted, we have built a more capable sensor capable of gathering (x,y,z) data



Figure 10. Comparison of methods of measurement of inter-landmark distances between landmarks seen in Figure 9 (shown as lines). Closed circles = correlation between range-sensor and caliper-based measurements; Open circles = correlation between projected video and caliper based measures. Open circles denoted by A are measures of distances between points 2 and 15 and 2 and 16; Open circles denoted by B are measures of distances between points 9 and 11 and 10 and 12. Note divergence due to foreshortening in these measurements. Circles may represent more than one measurement because of overlap.

Upon skeletonization, caliper based measures were taken by one of us (SGP) to the nearest 0.1 mm using a set of Fowler digital calipers connected to microcomputer using the convenient and flexible DataQ™ interface software. Landmark points (Figure 9) were selected (again by SGP) to insure a reasonable sampling of the 3-dimensional conformation of the skulls and to provide data on dimensions important to comparison with other scorpionfishes. Twenty-one measured distances among these landmark points were used to compare measuring techniques. The skulls were then subsequently measured for the same landmark points using the MorphoSys video digitization (Meacham 1993) using an Olympus 35 mm lens at the maximum possible working distances (50 to 70 cm) to minimize parallax, while providing a sufficiently large and clear image. Because some of the chosen measurements can not be visualized in a single plane, measurements were obtained from lateral, dorsal, and ventral projections.

## Comparison with Caliper and Projected Image Video Measurement

Data extracted from 3-D sensor based measurements and data taken for the same inter-landmark points using dial calipers were very nearly identical, with $r = 0.9995$

with a precision of 0.2–0.05 mm at about the same cost as the original sensor.

For measures of the kind described here, error due to perspective effects can be significant when measuring from projected 2-D imagery. Although MorphoSys was designed to measure plant leaf shapes, use of projected measurement of more 3-dimensional objects requires greater circumspection. Studies utilizing such measures to analyze shape must account for potential errors arising from perspective effects. Our results indicate that use of a single-plane structured-light range sensor can essentially eliminate errors due to perspective effects.

In our experiments we used only 21 of the more than 75,000 available points with estimated (x,y,z) coordinates per scan. Although these are sufficient to demonstrate the relative accuracy and considerable potential of this approach, we believe that future research will be usefully focused on developing automated methods capable of analyzing more numerous and more informative elements of the data set, thereby better characterizing subtle shape differences among objects. Such studies may lead to more objective methods of establishing landmarks among a neighborhood of potentially corresponding points. Such studies may also lead to more precise understanding of mechanisms, selection, and constraints that lead to and control shape differences. They may also aid in developing a better understanding how humans recognize taxonomically useful characters. However used, one of the greatest strengths of single-plane structured light sensing methods is that 3-D data from the rest of the scanned object remains readily available for display and a variety of additional new measurements become possible without subsequent rescanning of the original object.

Like 3-D data obtained from tomographic methods using other energy sources, these data can be archived and distributed electronically to provide relatively complete representations and to assure the same bases of comparison. See http://rvl4.ecn.purdue.edu/~cromwell/3d.html and http://lionfish.ims.usm.edu/~musweb/lasermeasure.html. Although limited to surface features, single-plane structured light imaging can secure data at relatively limited cost, unlike CT, PET, or NMRI imaging. By facilitating quantitative characterization and thus common understanding among scientists with a diverse range of perspectives, objects of common interest may be more accurately studied.

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# Utilization of Saltmarsh Shorelines by Newly Settled Sciaenids in a Texas Estuary

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# UTILIZATION OF SALTMARSH SHORELINES BY NEWLY SETTLED SCIAENIDS IN A TEXAS ESTUARY

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*ABSTRACT* Post-settlement patterns of habitat use along saltmarsh shorelines of Galveston Bay, Texas were examined for three sciaenids; spotted seatrout (*Cynoscion nebulosus*), red drum (*Sciaenops ocellatus*), and Atlantic croaker (*Micropogonias undulatus*). Collections were made summer through fall of 1997 and 1998 using a 1.5-m beam trawl hand-towed along the outside edge of salt marshes. Sciaenids were collected from tidal pass, bay, and remote tidal creek areas to assess large-scale (bay-wide) patterns of distribution and abundance. *Cynoscion nebulosus* were smaller and most numerous at bay stations, with densities peaking in June. Conversely, *S. ocellatus* were collected in higher numbers, and smaller sizes, at stations near the tidal pass, with peak densities in September. *Micropogonias undulatus* occurred in high numbers near both the tidal pass and remote tidal creeks, with undetectable size differences among areas and peak densities in November. Densities of *C. nebulosus* and *S. ocellatus* were greater at sites nearer the larval supply; patterns were less clear for *M. undulatus*. Small-scale patterns of habitat use were investigated within remote tidal creeks, with trends in density and size apparent for *M. undulatus*, while few *C. nebulosus* and *S. ocellatus* were collected. Interannual variability in densities occurred within and among stations, although total densities for each species were relatively similar between 1997 and 1998.

## INTRODUCTION

Estuarine saltmarshes are productive systems utilized by many commercially important fishes and shellfishes (Nixon and Oviatt 1973, Zimmerman and Minello 1984, Cowan and Birdsong 1985, Day et al. 1989, Hettler 1989, Deegan 1993, Rozas and Minello 1998), and are known to play an important role in the development of many species (Ayvazian et al. 1992, Rountree and Able 1992, Kneib 1997, Peterson et al. 2000). It is generally thought that larval and juvenile fishes benefit from increased prey resources and/or from decreased predation pressure, although the relative contribution of each remains unclear (Boesch and Turner 1984). Saltmarsh edge, or shoreline, provides a foraging area for nekton and access to the marsh interior where nekton can forage during high tide (Rozas and Hackney 1984, Kneib and Wagner 1994, Minello et al. 1994). Moreover, structure provided by vegetation may serve as a refuge from predators (Minello and Zimmerman 1983, Stunz 1999).

Depending upon the spatial scale examined, different processes can be important in determining patterns of settlement and habitat use (Booth and Brosnan 1995, Caley et al. 1996). Within estuaries, high spatial variability in recruitment density at small scales (m's) can result from habitat choice, while lower variability at larger scales (km's) is affected more by larval delivery (Bell and Westoby 1986). High spatial and temporal variability in density at even larger scales (10's of km)

can result from the patchy nature of planktonic larvae (Bell and Westoby 1986, Doherty 1991, Tolimieri 1995). Habitat location and exposure can also affect recruitment levels, with higher recruitment to areas with increased exposure to currents (Gaines and Roughgarden 1985). On smaller scales, a form of recruitment limitation occurs when downcurrent areas receive fewer recruits than upcurrent areas (Olson 1985). This hypothesis, important in structuring fish assemblages among seagrass beds (Bell and Westoby 1986), has not been fully examined in saltmarshes.

The purpose of this study was to examine how the location of saltmarshes within a bay relates to patterns of habitat use. To accomplish this, patterns of distribution and abundance were examined for larvae and juveniles of 3 commercially important sciaenid species; spotted seatrout *Cynoscion nebulosus* (Cuvier), red drum *Sciaenops ocellatus* (Linnaeus), and Atlantic croaker *Micropogonias undulatus* (Linnaeus). The contrasting life history strategies of these species (*C. nebulosus* spawn within estuaries, *S. ocellatus* spawn nearshore, and *M. undulatus* spawn offshore; Johnson 1978) allowed us to examine the effects that spawning location may have on recruitment to various nursery areas. At a bay-wide scale (10's of km), densities and sizes of larval and juvenile sciaenids were compared among saltmarsh shorelines of tidal pass, bay, and remote tidal creek areas. Also at this large scale, we examined the abundance of sciaenids within a relatively similar habitat at varying distances from the tidal pass. At a smaller scale

(1-2 km), we assessed densities and size frequencies of young sciaenids at differing distances along tidal creeks within a saltmarsh complex. Finally, densities from the fall of both 1997 and 1998 were examined to evaluate interannual variability.

## MATERIALS AND METHODS

### Study site

Sampling was conducted along saltmarsh shorelines of West Galveston Bay in the Galveston Bay complex, Texas (Figure 1). The Galveston Bay complex is a large barrier-built estuary that experiences mixed tides with a tidal range of 0.2 to 0.4 m (Britton and Morton 1989, White et al. 1993). Tides are often modified by meteorological forcing that create periods of sustained high water in spring and fall, while winter water heights are below mean levels (Rozas 1995). Tidal exchange for the far eastern portion of West Galveston Bay occurs through Bolivar Roads (tidal pass), while San Luis Pass provides tidal exchange for the western portion of the bay, including the sampling locations of this experiment (Texas Department of Water Resources 1982). All references in
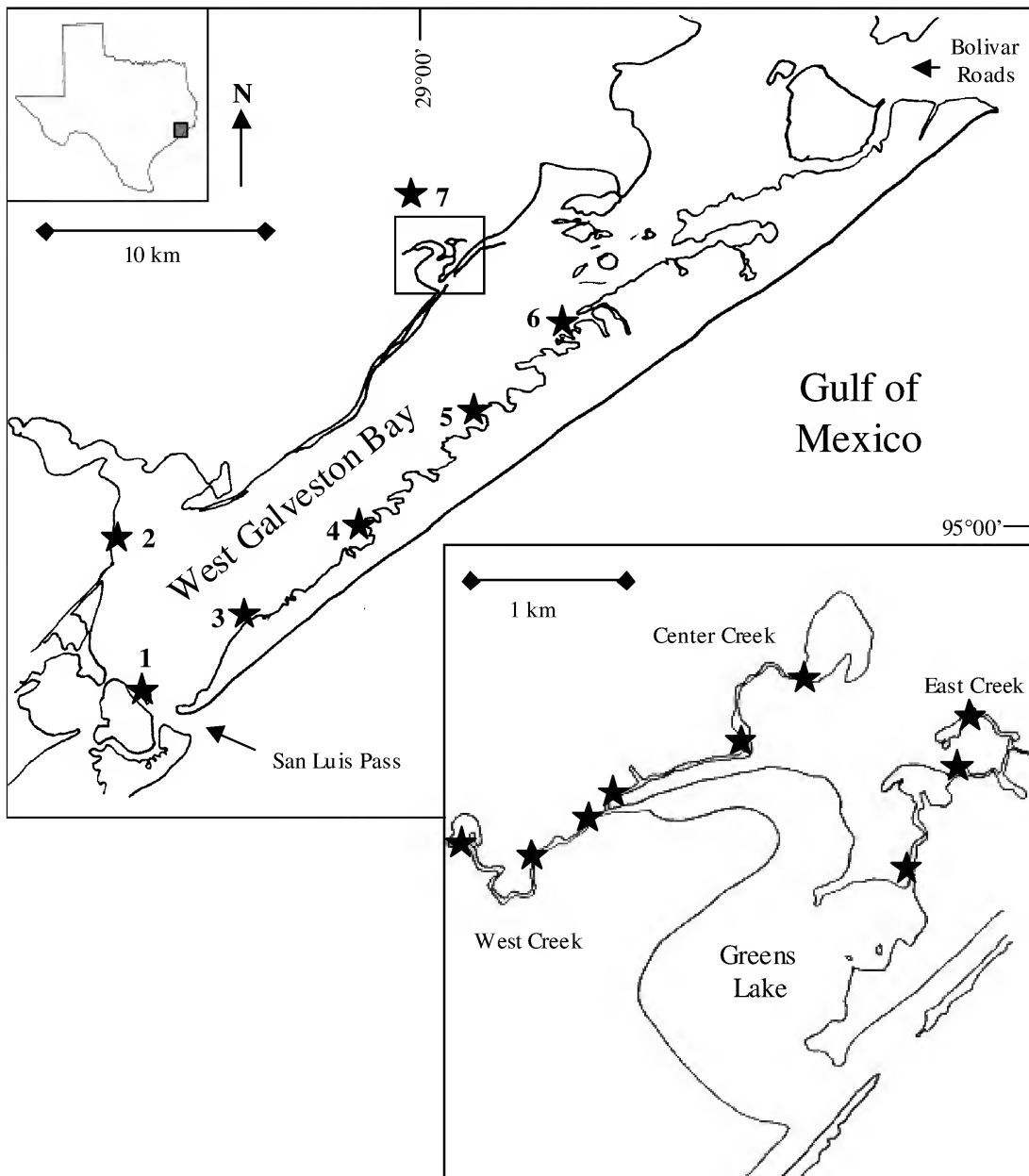


Figure 1. Location of sampling stations along saltmarsh shorelines within the West Galveston Bay complex. Tidal pass (1–3), bay (4–6), and tidal creek (7) stations are shown in the first inset. The second inset gives the substations located at the front, mid, and back of 3 tidal creeks in Greens Lake.

this paper to 'tidal pass' refer to San Luis Pass. The low marsh, dominated by smooth cordgrass *Spartina alterniflora* (Loisel), on the southern shoreline of West Galveston Bay is usually 10–50 m wide, while the north shoreline consists of spoil banks with sparse amounts of *S. alterniflora*, and 5 satellite bays surrounded by expansive saltmarsh complexes. Greens Lake is a small (about 2.25 km²) satellite bay separated from West Galveston Bay by the Intracoastal Canal Waterway. The saltmarsh complex around Greens Lake is over 3.75 km² and surrounds the east, north, and west shorelines of the bay. Three similar tidal creek channels, each over 1.5 km in length, extend from Greens Lake into the marsh complex and terminate in large, shallow (mean depth < 0.5 m) expanses of open water. All 3 channels branch often, connecting to numerous pools, creeks, and ponds. The 3 channels are bordered by *S. alterniflora* in areas with low elevations, while maritime saltwort *Batis maritima* (Linnaeus) and Carolina wolfberry *Lycium carolinianum* (Walter) dominate at slightly higher elevations, generally along steep banks.

## Sampling design

Collections were made monthly, May through December in 1997, and twice monthly September through December in 1998 at Stations 1–6 around the bay shoreline, ranging from 2–25 km in distance from the tidal pass, and at 3 tidal creeks of Greens Lake (Station 7). Each tidal creek was stratified into 3 sampling sections (front, mid, and back) based on distance along creek channels, creating a total of 9 tidal creek substations. No collections were made at Station 6 during the first month of sampling in May 1997, and no collections were made at tidal creek Station 7 in June 1997 or December of 1997 or 1998.

Large-scale variation in habitat use patterns by sciaenids was examined among 3 marsh-edge areas at differing locations within West Galveston Bay in 1997. Sampling stations were grouped into 1) pass (Stations 1–3), 2) bay (Stations 4–6), and 3) tidal creek (Station 7, pooling all 9 Greens Lake substations). The effect of distance from a tidal pass on marsh use by sciaenids was investigated using 4 similar stations (Station 3 = 5 km, Station 4 = 11 km, Station 5 = 19 km, and Station 6 = 25 km) that were in a linear transect along the south shoreline of West Galveston Bay in 1997. Front, mid, and back tidal creek substations in Greens Lake were compared in 1997 to assess small-scale patterns of habitat use. The order that shoreline stations and tidal creek substations were sampled was chosen randomly. Mean densities for each station, taken September through November of

1997 and 1998, were used to qualitatively compare interannual variability. Due to differences in sampling intensity and duration, no statistical analyses were made comparing 1997 and 1998 densities.

Larval and juvenile fishes were collected using a 1.5-m wide hand-towed beam trawl (Renfro 1963) constructed with a 1.6-mm mesh body and 750-$\mu$m mesh codend. At each station, three 15-m tows (22.5 m² tow⁻¹) were taken within 1-m of the saltmarsh shoreline, with the exact site within the sampling station chosen haphazardly. The beam trawl was placed on the substrate and a line was walked out in an arc to avoid disturbing the area to be sampled. The trawl was then retrieved at about 1.5 m sec⁻¹ parallel to the vegetation line. Gear avoidance is a potential problem with moderate sized (< 2-m wide) trawl and sled gears (Rooker et al. 1999). Consequently, capture efficiency of the beam trawl may vary as a function of trawl size, and thus densities of the larger individuals may be biased.

The catch was washed into the codend and sorted in a 500-$\mu$m sieve. Sciaenids were preserved in 70% ethanol and standard length (SL) was later measured to the nearest 0.01 mm using a stereoscope and Optimas 6.2 image analysis software. Larval and juvenile sciaenids were identified to species following descriptions of Ditty and Shaw (1994) and were separated into 2 size groups based on size-frequency histograms to delineate new settlers (< 10 mm SL) from post-settlers ($\geq$ 10 mm SL).

Several environmental variables were measured at each sampling station or substation. Temperature and salinity were measured with a thermometer and either a refractometer or a digital salinity meter, respectively. Tow depth was measured with a meter stick placed at a random point along the towpath of each trawl and water depth in the adjacent vegetation was recorded. Five 0.5 m² quadrats were randomly thrown within each sampling station or substation to determine percent cover of emergent vegetation.

## Data analysis

Fish densities (x + 1) and lengths (x) were *ln*-transformed to minimize heteroscedasticity and normalize data. Harltley's test indicated that heteroscedasticity was still present (Ott 1993); however, analysis of variance (ANOVA) is robust to departures of variance homogeneity and results are unlikely to be compromised (Zar 1984). To examine large-scale habitat use patterns, we used a two-factor ANOVA to test for the separate and interactive effects of area (pass, bay, and tidal creek) and time on sciaenid densities. Because the June sampling period was excluded in this test, another ANOVA was

performed using only pass and bay stations including June. Test results were similar to the ANOVA excluding June, so only results from the former test are presented. A two-factor ANOVA tested for the effects of area (pass, bay, and tidal creek) and time on sciaenid lengths, with time blocked. To examine the effects of distance from the tidal pass (Stations 3–6) and time on densities, we used a two-factor ANOVA with interaction. Small-scale patterns of habitat use within tidal creeks were examined using a three-factor ANOVA with time blocked to test the effects and interactions of creek (west, center, east) and section (front, mid, back) on sciaenid densities. A significance level of $\alpha = 0.05$ was used for all statistical tests with significant differences among means separated a posteriori with either Tukey's HSD for density comparisons or Sheffé's procedure for length comparisons. Relationships between density and temperature, salinity, water depth at vegetation line, tow depth, and percent cover of emergent vegetation were examined separately for each species during the month of peak abundance with Pearson's correlation. Data analysis was performed using SYSTAT 8.0 (SPSS 1998).

## RESULTS

### Environmental conditions

Water temperature and salinity varied among stations and seasonally (Table 1). Late spring temperatures were 26–30°C, rose to 34–35°C in summer and then dropped to 17–20°C in late fall to early winter. Bay stations were generally 1–3°C higher than tidal creek or pass stations in the summer and 1–2°C lower in late fall to early winter. Maximum range in temperature recorded over the sampling season was 21°C, from a peak high

recorded in August (37°C) to the lowest December value (16°C). Although salinity was variable, seasonal trends were apparent; salinities were low in the late spring (14–18‰), increased during the summer (31–34‰), and then dropped again in the fall (21–26‰). During the spring, bay and tidal creek stations were about 4‰ lower than pass stations. Although summer salinities were similar among areas, fall salinities at the tidal creek station were about 5–6‰ lower than bay and pass stations. Salinity values measured during this study ranged from 36‰ in August to 10‰ in May.

### Fish assemblage

A diverse assemblage of fishes, from a total of 22 families was caught in 1997 (Table 2). Four families (Sciaenidae, Gobiidae, Engraulidae, and Atherinidae) comprised over 76% of the total catch. The most numerous species included naked goby Gobiosoma bosc (Lacepède), darter goby Gobionellus boleosoma (Jordan and Gilbert), bay anchovy Anchoa mitchilli (Valenciennes), inland silverside Menidia beryllina (Cope), and 2 sciaenids (M. undulatus and C. nebulosus).

A total of 8 sciaenid species was collected during the 1997 sampling period (Table 3). The 3 most abundant, M. undulatus, C. nebulosus, and S. ocellatus, accounted for over 88% of sciaenids collected. Silver perch Bairdiella chrysoura (Lacepède) occurred in samples from May through July with numbers peaking in July, while spot Leiostomus xanthurus (Lacepède) were collected at the end of sampling in December. Sand seatrout Cynoscion arenarius (Ginsburg) and southern kingfish Menticirrhus americanus (Lacepède) were collected during the summer and fall in limited numbers, and a single black drum Pogonias cromis (Linnaeus) was col-

## TABLE 1

Monthly mean (± 1 SE) water temperature (°C) and salinity (‰) values from saltmarsh shorelines at tidal pass (Stations 1–3), bay (Stations 4–6), and tidal creek (Station 7) stations in West Galveston Bay, Texas, May–December 1997. NA = not available.

| Month | Pass area | | Bay area | | Tidal creek | |
| | Temperature | Salinity | Temperature | Salinity | Temperature | Salinity |
|---|---|---|---|---|---|---|
| May | 27.5(0.15) | 18.5(0.92) | 30.5(0.22) | 14.0(1.79) | 26.5(0.49) | 14.1(0.21) |
| June | 31.3(0.45) | 26.4(1.42) | 30.2(0.08) | 21.8(1.48) | NA | NA |
| July | 34.8(0.38) | 31.8(0.73) | 34.5(0.34) | 31.0(0.29) | 33.2(0.09) | 31.4(0.26) |
| August | 34.0(0.21) | 32.0(1.26) | 35.1(0.13) | 33.4(0.41) | 33.9(0.30) | 32.0(0.21) |
| September | 31.5(0.22) | 31.5(0.90) | 32.8(0.33) | 32.6(0.20) | 29.6(0.26) | 25.3(0.17) |
| October | 26.0(0.29) | NA | 24.7(0.44) | NA | 24.6(0.77) | 21.9(0.07) |
| November | 20.8(0.36) | 25.4(0.82) | 18.8(0.26) | 25.5(0.38) | 19.9(0.31) | 21.5(0.17) |
| December | 17.3(0.44) | 25.2(1.83) | NA | NA | NA | NA |

## TABLE 2

**The number and percent composition of fishes (by family) collected with a 1.5-m beam trawl from saltmarsh shorelines in West Galveston Bay, Texas, May–December 1997.**

| Family | Number | Percent |
|--------|--------|---------|
| Sciaenidae | 1141 | 25.45 |
| Gobiidae | 999 | 22.28 |
| Engraulidae | 688 | 15.35 |
| Atherinidae | 612 | 13.65 |
| Clupeidae | 282 | 6.29 |
| Gerreidae | 223 | 4.97 |
| Soleidae | 212 | 4.73 |
| Syngnathidae | 123 | 2.74 |
| Cyprinodontidae | 64 | 1.43 |
| Sparidae | 31 | 0.69 |
| Bothidae | 16 | 0.36 |
| Triglidae | 13 | 0.29 |
| Lutjanidae | 9 | 0.20 |
| Synodontidae | 4 | 0.09 |
| Ephippidae | 3 | 0.07 |
| Mugilidae | 3 | 0.07 |
| Antennariidae | 2 | 0.04 |
| Balistidae | 2 | 0.04 |
| Elopidae | 1 | 0.02 |
| Ophichthidae | 1 | 0.02 |
| Carangidae | 1 | 0.02 |
| Lobotidae | 1 | 0.02 |
| Unidentified larvae | 52 | 1.16 |
| Total | 4483 | 100 |

lected in August.

### Size distribution

*Sciaenops ocellatus* and *C. nebulosus* occurred as small as 5 mm, while the smallest *M. undulatus* collected were 7 mm (Figure 2). The most frequent sizes of *C. nebulosus* and *M. undulatus* collected were 9–11 and 9–12 mm, respectively. Conversely, the most abundant size of *S. ocellatus* was 6–8 mm. *Cynoscion nebulosus* occurred in collections at all 1-mm size classes up to 33 mm, while few *S. ocellatus* or *M. undulatus* collected were over 16 mm. Collectively, over 98% of all 8 sciaenid species collected were under 30 mm, with the largest individual 56 mm (*P. cromis*).

### Seasonal variability

*Cynoscion nebulosus* occurred in collections from May to October, while *S. ocellatus* and *M. undulatus*

were present from September to November, and October to December, respectively (Figure 3). Densities of *C. nebulosus* < 10 mm were highest in June (44.9%), the month that also had the highest mean (± 1 SE) monthly density (0.44 ± 0.245 $m^{-2}$). Peak tow densities of *C. nebulosus* in June were 4.71 $m^{-2}$. A minor second peak in *C. nebulosus* density occurred in September with 89% of the catch composed of individuals ≥ 10 mm. *Sciaenops ocellatus* < 10 mm comprised 96% of the peak September catch, which had a mean monthly density of 0.09 ± 0.059 $m^{-2}$. Tow densities as great as 2.71 $m^{-2}$ were collected for *S. ocellatus* in September. Unlike *C. nebulosus* and *S. ocellatus*, the highest proportion of *M. undulatus* < 10 mm (44.8%) was collected in October, not during the peak month of November which had a monthly mean density of 0.31 ± 0.098 $m^{-2}$ and peak tow densities of 3.38 $m^{-2}$.

### Environmental correlations

Positive correlations between densities and environmental variables occurred for each species (Table 4). *Cynoscion nebulosus* showed significant positive correlations with temperature, salinity, tow depth, and percent cover of emergent vegetation. *Sciaenops ocellatus* showed significant positive correlations with percent cover of emergent vegetation, tow depth, and water depth at vegetation line. Significant positive correlations occurred for *M. undulatus* densities with tow depth and percent cover of emergent vegetation.

### Large-scale patterns of habitat use

Large-scale variation in habitat use was observed for all 3 species among the pass, bay, and tidal creek stations. Mean (± 1 SE) densities of both *C. nebulosus* (ANOVA, $F_{2,312}$ = 30.381, $P < 0.001$) and *S. ocellatus* (ANOVA, $F_{2,312}$ = 12.205, $P < 0.001$) differed significantly among stations. Densities of *C. nebulosus* were higher at the bay (0.07 ± 0.014 $m^{-2}$) stations than pass (0.02 ± 0.005 $m^{-2}$) or tidal creek (0.01 ± 0.001 $m^{-2}$) stations (Tukey HSD, $P < 0.05$). *Sciaenops ocellatus* densities were higher at the pass (0.06 ± 0.034 $m^{-2}$) stations than at bay or tidal creek stations, each with densities less than 0.01 $m^{-2}$ (Tukey HSD, $P < 0.05$). Although densities of *M. undulatus* were greater at the pass (0.10 ± 0.049 $m^{-2}$) and tidal creek (0.07 ± 0.028 $m^{-2}$) stations than at the bay (0.01 ± 0.002 $m^{-2}$) stations, the pattern was not significant (ANOVA, $F_{2,312}$ = 1.838, $P = 0.161$). Significant interactions between area and time were found for all 3 species, indicating that changes in densities among stations were not consistent over time.

## TABLE 3

**Number, percent frequency, and sizes (SL) of sciaenids caught from saltmarsh shorelines in West Galveston Bay, Texas, May–December 1997. Percent composition based on total number of sciaenids collected.**

| Common name | Species | Number | Percent | Mean size (mm) | Size range (mm) |
|---|---|---|---|---|---|
| Atlantic croaker | *Micropogonias undulatus* | 443 | 38.83 | 11.1 | 7.6–22.4 |
| Spotted seatrout | *Cynoscion nebulosus* | 438 | 38.39 | 13.3 | 5.4–38.0 |
| Red drum | *Sciaenops ocellatus* | 131 | 11.48 | 8.9 | 5.2–38.5 |
| Silver perch | *Bairdiella chrysoura* | 77 | 6.75 | 9.5 | 4.7–35.4 |
| Spot | *Leiostomus xanthurus* | 37 | 3.24 | 10.2 | 8.5–13.9 |
| Sand seatrout | *Cynoscion arenarius* | 9 | 0.79 | 14.6 | 4.7–31.1 |
| Southern kingfish | *Mentcirrhus americanus* | 5 | 0.44 | 11.0 | 9.4–13.3 |
| Black drum | *Pogonias cromis* | 1 | 0.09 | 56.0 | 56.0 |

Patterns in size distributions and means also differed among the pass, bay, and tidal creek stations (Figure 4). Mean (± 1 SE) size of both *C. nebulosus* (ANOVA, $F_{2,160} = 5.050$, $P = 0.007$) and *S. ocellatus* (ANOVA, $F_{2,108} = 33.460$, $P < 0.001$) differed significantly among stations. Mean size of *C. nebulosus* was greater in the tidal creek ($24.6 ± 1.76$ mm) station than in pass ($14.4 ± 1.09$ mm) or bay ($17.5 ± 0.61$ mm) stations (Sheffé, $P < 0.05$). Similar to *C. nebulosus*, mean size of *S. ocellatus* from the tidal creek ($19.5 ± 2.75$ mm) station was greater than from pass ($7.8 ± 0.29$ mm) or bay ($9.3 ± 0.43$ mm) stations (Sheffé, $P < 0.05$). No significant difference in mean size of *M. undulatus* was detected among stations (ANOVA, $F_{2,428} = 2.694$, $P = 0.070$), with sizes ranging from $11.0 ± 0.01$ mm at the pass stations to $12.8 ± 1.18$ mm at the bay stations.

Densities of *C. nebulosus* (ANOVA, $F_{3,89} = 67.933$, $P < 0.001$) and *S. ocellatus* (ANOVA, $F_{3,89} = 6.120$, $P = 0.001$) varied among stations (Stations 3–6) as a function of distance from the tidal pass (Figure 5). Mean (± 1 SE) densities of *C. nebulosus* were significantly higher at the station farthest from the tidal pass (Station 6) than at other stations (Tukey HSD, $P < 0.05$). Similarly, densities of *S. ocellatus* were significantly higher at Station 6 (Tukey HSD, $P < 0.05$). The highest density of *M. undulatus* was found at the station closest to the tidal pass (Station 3); however, only 12 *M. undulatus* were collected from the 4 stations used and no statistical analysis was performed. Significant interactions between station and time were present for *C. nebulosus* and *S. ocellatus*. Slight increases in density of *C. nebulosus* were seen at all 4 stations during the September peak, but only Station 6 increased in density during the June peak ($3.88 ± 0.544$ m$^{-2}$). September densities of *S. ocellatus*

were highest at Station 5 while Station 6 had the highest densities in October.

### Small-scale patterns within a tidal creek

Densities of *C. nebulosus* and *S. ocellatus* were too low for statistical analysis, although the majority of individuals for both species were captured at the front of tidal creeks (Figure 6). Mean (± 1 SE) densities of *M. undulatus* were relatively similar between front ($0.08 ± 0.063$ m$^{-2}$) and back ($0.12 ± 0.057$ m$^{-2}$) substations of the tidal creeks, both areas having nonsignificantly higher densities than mid ($0.01 ± 0.002$ m$^{-2}$) substations (ANOVA, $F_{2,148} = 2.614$, $P = 0.077$). Small-scale differences in mean size occurred for *M. undulatus* (ANOVA, $F_{2,234} = 69.933$, $P < 0.001$); fish from front substations were smaller ($9.6 ± 0.12$ mm) than fish from either mid ($12.9 ± 1.63$ mm) or back ($12.2 ± 0.18$ mm) substations (Sheffé, $P < 0.05$).

### Interannual variability

Interannual variability in densities occurred within and among stations, although total densities for each species were relatively similar between 1997 and 1998 (Table 5). The spatial pattern of habitat use of *C. nebulosus* in 1998 mirrored 1997, although it shifted slightly toward the tidal pass; Stations 4 and 6 had peak densities in 1997 while Stations 3 and 5 had the peaks in 1998. Densities of *S. ocellatus* in 1997 were highest at Station 2, while the station closest to the tidal pass (Station 1) had the highest densities in 1998. The remaining pass and bay stations had higher densities of *S. ocellatus* in 1998 than in 1997. *Cynoscion nebulosus* and *S. ocellatus* were caught infrequently in tidal creeks in both 1997 and 1998. Similar to *S. ocellatus*, mean densities of *M. undulatus* increased at bay stations in 1998. Tidal creek densities of *M. undulatus* were higher than for *C.*
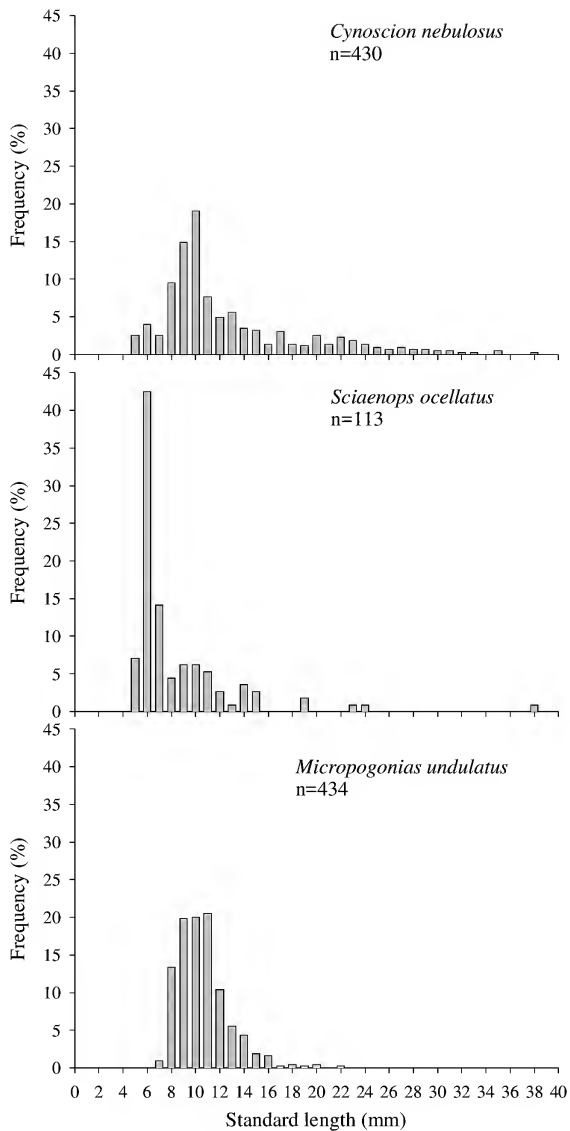
**Figure 2. Size frequency (1-mm size classes) of 3 species of sciaenids collected monthly May–December 1997, from saltmarsh shorelines of West Galveston Bay, Texas.**
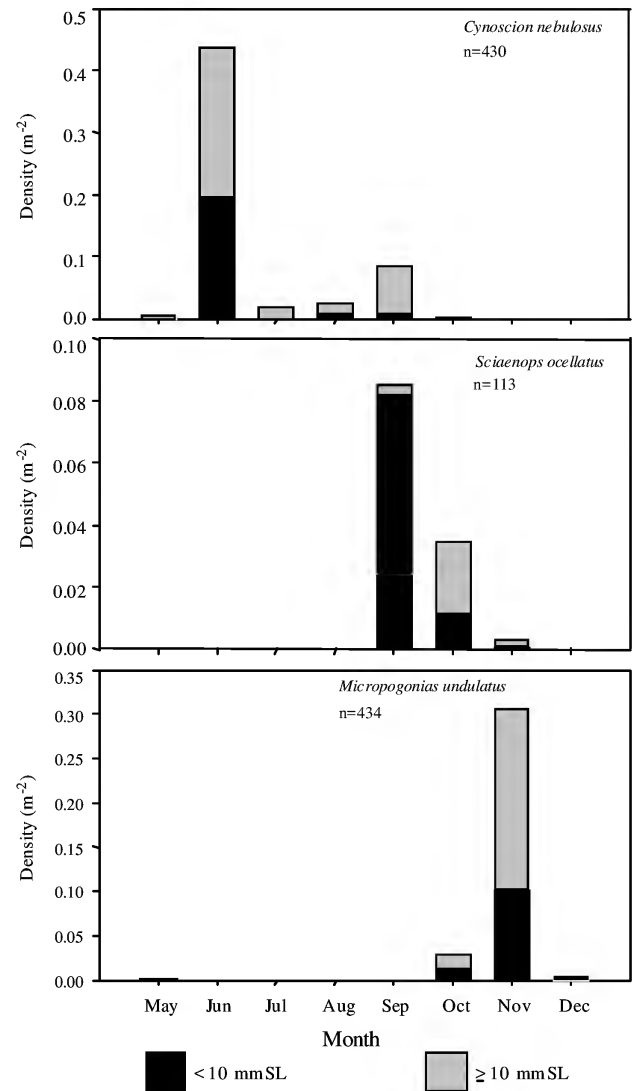


**Figure 3. Monthly mean densities for 3 species of sciaenids from saltmarsh shorelines of West Galveston Bay, Texas, 1997. Two size classes (< 10 mm SL, and ≥ 10 mm SL) are shown. Y-axis scales differ among graphs.**

*nebulosus* or *S. ocellatus*, and decreased slightly between 1997 and 1998.

## DISCUSSION

Ichthyofauna utilizing saltmarsh shorelines of West Galveston Bay during this study were typical for Gulf of Mexico (Peterson and Ross 1991, Rakocinski et al. 1992, Kneib 1997, Rozas and Minello 1998, Minello 1999, Peterson et al. 2000) and southeastern Atlantic coast (Shenker and Dean 1979, Weinstein 1979, Kneib 1997) saltmarshes. Following Peterson and Turner's (1994) classification, all 4 categories of the saltmarsh fish community were present in this study, although interior

marsh residents and interior marsh users, represented primarily by cyprinodontids, were poorly represented (< 2% of the individuals caught). Numerically, edge marsh users were the dominant group containing both marsh residents such as gobiids, and estuarine-dependent species represented by sciaenids. Subtidal marsh users included soleids as well as the seasonally abundant atherinids, engraulids, and clupeids.

Densities of *C. nebulosus*, *S. ocellatus*, and *M. undulatus* in the present study ranged from similar (Rozas and Minello 1998, Minello 1999) to an order of magnitude lower than (Rakocinski et al. 1992, Baltz et al. 1993) densities found in similar shoreline habitats on the western Gulf coast. Although densities of *C. nebulosus* from

## Table 4

**Results of Pearson's correlation for densities of *Cynoscion nebulosus* and *Sciaenops ocellatus* from September 1997 and *Micropogonias undulatus* from November 1997, the months of peak abundance for each species. Species values are from ln (x + 1) transformed densities. \* = significant results ($P < 0.05$). The units for environmental variables can be found in materials and methods.**

| n = 39 | C. nebulosus | Temperature | Salinity | Veg. Depth | Depth | Percent cover |
|---|---|---|---|---|---|---|
| C. nebulosus | 1.000 | | | | | |
| Temperature | 0.619* | 1.000 | | | | |
| Salinity | 0.666* | 0.742* | 1.000 | | | |
| Veg. Depth | 0.152 | 0.123 | 0.151 | 1.000 | | |
| Depth | 0.415* | 0.200 | 0.183 | 0.614* | 1.000 | |
| Percent cover | 0.374* | 0.316* | 0.342* | 0.941* | 0.804* | 1.000 |

| n = 39 | S. ocellatus | Temperature | Salinity | Veg. Depth | Depth | Percent cover |
|---|---|---|---|---|---|---|
| S. ocellatus | 1.000 | | | | | |
| Temperature | 0.188 | 1.000 | | | | |
| Salinity | 0.127 | 0.742* | 1.000 | | | |
| Veg. Depth | 0.499* | 0.123 | 0.151 | 1.000 | | |
| Depth | 0.409* | 0.200 | 0.183 | 0.614* | 1.000 | |
| Percent cover | 0.512* | 0.316* | 0.342* | 0.941* | 0.804* | 1.000 |

| n = 63 | M. undulatus | Temperature | Salinity | Veg. Depth | Depth | Percent cover |
|---|---|---|---|---|---|---|
| M. undulatus | 1.000 | | | | | |
| Temperature | −0.055 | 1.000 | | | | |
| Salinity | 0.031 | −0.012 | 1.000 | | | |
| Veg. Depth | 0.258 | 0.050 | 0.120 | 1.000 | | |
| Depth | 0.379* | −0.177 | 0.003 | 0.500* | 1.000 | |
| Percent cover | 0.318* | 0.039 | 0.169 | 0.950* | 0.707* | 1.000 |

saltmarsh shorelines were also similar to densities reported from Texas seagrass beds, densities of both *S. ocellatus* and *M. undulatus* from shorelines were several fold lower than from seagrass beds (Rooker et al. 1998, Stunz 1999). Nevertheless, differences in sampling duration and gear types between studies may affect density estimates, making direct comparisons difficult.

Three sciaenid species examined in this study appeared to settle from the plankton into saltmarsh shorelines. *Cynoscion nebulosus* and *S. ocellatus* first appeared in saltmarsh edges at a relatively small size (5 mm), consistent with the smallest sizes of these species collected from seagrass beds in the Gulf (Peters and McMichael 1987, McMichael and Peters 1989, Rooker et al. 1999, Stunz 1999). Peaks in size frequency histograms for *C. nebulosus* (about 10 mm) and *S. ocellatus* (about 6 mm) are similar to other studies, suggesting that these 2 species have fully recruited (i.e., switched from a planktonic to a demersal phase) to saltmarsh shorelines by about 10 mm (Rooker et al. 1998, Stunz 1999).

Although McMichael and Peters (1989) state that *C. nebulosus* under 15 mm may not be fully recruited to estuarine habitats of Tampa Bay, this difference may reflect the deeper waters sampled in their study. Recent research shows that at least some *S. ocellatus* spawn closer inshore than previously thought, often spawning near the end of jetties (S. Holt personal communication), or just outside of tidal passes (Murphy and Taylor 1990). This could result in some recruits entering bays earlier, at sizes closer to that of estuarine-spawned *C. nebulosus*. Larger sizes of *M. undulatus* at both first occurrence and at peak numbers may be attributable to longer larval duration. *Micropogonias undulatus* spawn farther offshore in the Gulf of Mexico than the other 2 species, generally more than 50 km from shore (Cowan and Shaw 1988, Ditty et al. 1988), resulting in planktonic durations of 60–90 days (Cowan and Shaw 1988).

Seasonal occurrence of sciaenids found in the present study was similar to that for the same species found in other estuarine areas of the Gulf (Peters and McMichael
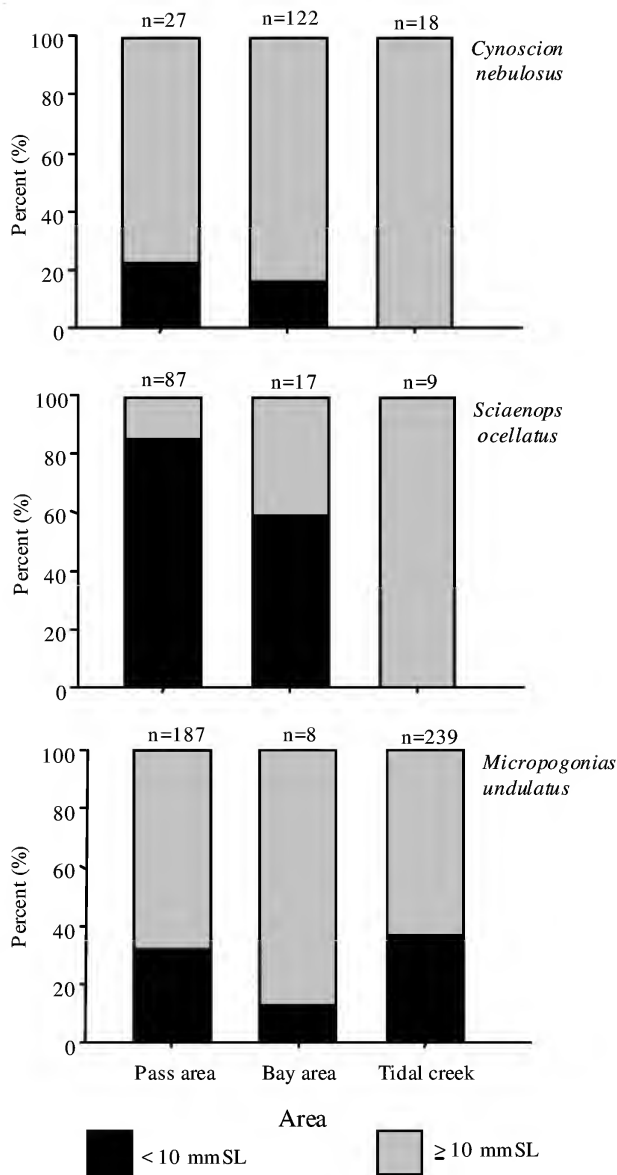
Figure 4. Percent composition of 2 size classes (< 10 mm SL, and ≥ 10 mm SL) for 3 sciaenid species collected from saltmarsh shorelines at pass, bay, and tidal creek stations of West Galveston Bay, Texas, May–November (excluding June) 1997.
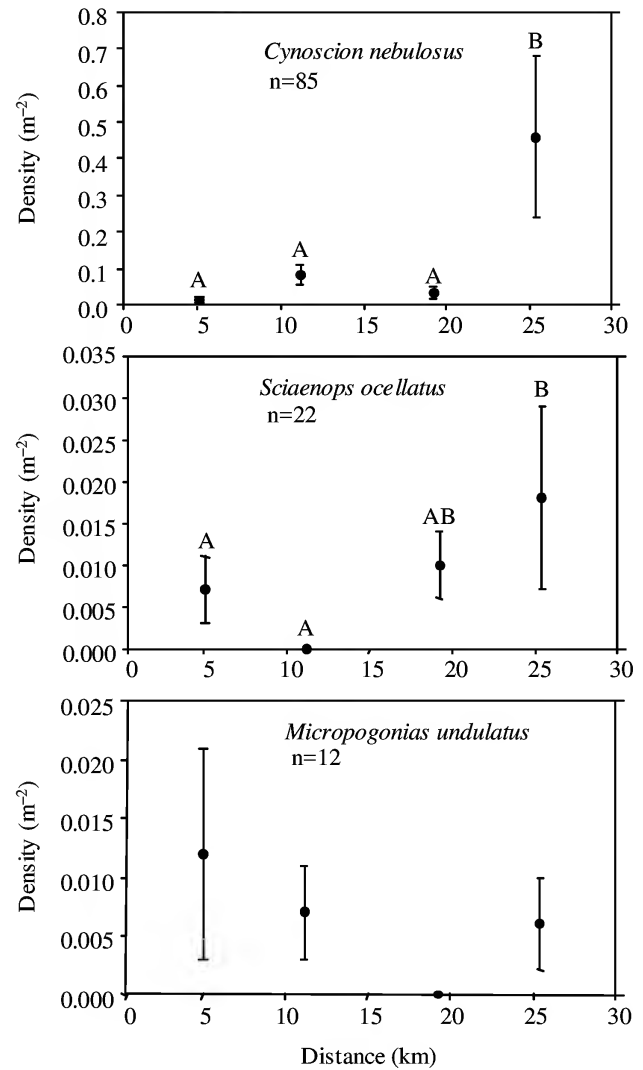


Figure 5. Mean densities (± 1 SE) for 3 sciaenid species collected from saltmarsh shorelines at varying distances from the tidal pass in West Galveston Bay, Texas. Collections were taken June–December 1997. Letters denote significantly different mean values (Tukey HSD).

1987, McMichael and Peters 1989, Rooker et al. 1998, Stunz 1999, Peterson et al. 2000) and southeastern Atlantic (Shenker and Dean 1979, Rogers et al. 1984, Nixon and Jones 1997) coasts. Water temperature may be an important factor influencing when sciaenids leave saltmarsh shorelines. In the present study, *C. nebulosus* and *S. ocellatus* became scarce in collections when water temperatures dropped to 25°C and 20°C, respectively; similar to findings from the Everglades (Jannke 1971). Experiments have shown that juvenile *S. ocellatus* become inactive at 20°C (Holt et al. 1981), and Chao and Musick (1977) suggest that water temperature is a criti-

cal factor determining when sciaenids (including *C. nebulosus* and *M. undulatus*) emigrate from nursery areas to deeper waters. Positive correlations of density with water temperature for *C. nebulosus* support this idea, although significant correlations with temperature were not apparent for the other two species.

*Cynoscion nebulosus* and *S. ocellatus* occupied different areas of the bay; however, both species were most abundant at stations nearest their putative spawning grounds (bay stations and pass stations, respectively). Small sizes of *C. nebulosus* and *S. ocellatus* found at these stations suggest that these species settle at the first suitable site encountered. Larger *C. nebulosus* and *S. ocellatus* taken from tidal creeks may indicate that post-
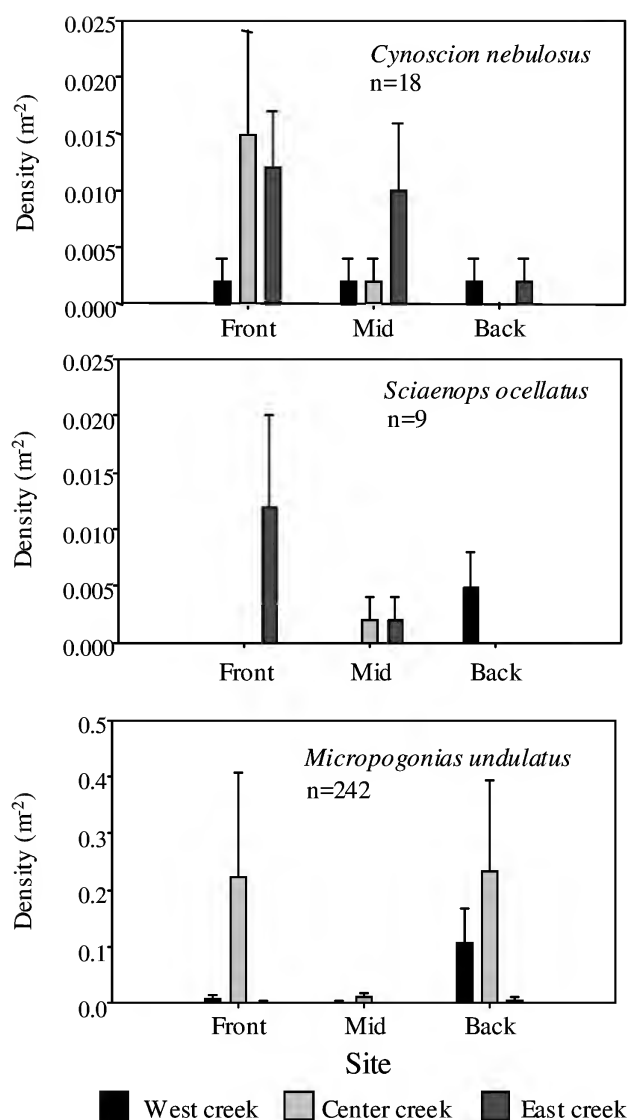
Figure 6. Mean densities (± 1 SE) for 3 species of sciaenids collected from saltmarsh shorelines at different sections of tidal creeks in the Greens Lake saltmarsh complex of West Galveston Bay, Texas, May–November (excluding June) 1997.

settlement migration to tidal creeks occurs after settlement in other areas, similar to a pattern described for *S. ocellatus* in Tampa Bay where settlement occurs along bay shorelines with later migration to backwater areas (Peters and McMichael 1987). Although high densities of *M. undulatus* at the pass area are consistent with the idea of settlement nearest spawning areas, the high number of individuals < 10 mm captured at tidal creek stations indicates that other factors are involved. On the Atlantic Coast, *M. undulatus* larvae utilize bottom currents to migrate from offshore to inshore (Hettler and Hare 1998), and continue to use up-estuary bottom flows to reach settlement sites near the estuary head (Weinstein

et al. 1980, Pietrafesa and Janowitz 1988, Nixon and Jones 1997). Individuals employing this strategy may maintain their position in the channel during transport to settlement sites and thus not utilize intermediate sites along the marsh edge. *Micropogonias undulatus* densities in West Galveston Bay appeared to follow this pattern.

Densities of *C. nebulosus* increased with distance from the tidal pass, consistent with the trend of increased numbers near the suspected spawning source. Similarly, *M. undulatus* densities were higher at stations closer to the suspected spawning source (pass stations), although within-station variability was high and results were not significant. *Sciaenops ocellatus* densities exhibited a trend opposite of that expected (higher densities farther from the larval source); however, a limited sample size and high within-station variability occurred in collections. Possible causes for this high variability may be due to wave energy and wind-driven currents that can cause variability in estuarine recruitment, especially in shallow barrier-built estuaries (Miller 1988, Dirnberger 1993, Jenkins et al. 1996, Jenkins et al. 1998, Xie and Eggleston 1999). For example, highest numbers of newly settled *C. nebulosus* were collected from an exposed point, in which hundreds of larval gobiids and engraulids were also collected, suggesting that wind-driven currents may influence the delivery of larval fishes.

On small spatial scales, movement of new recruits can modify initial settlement patterns (Baltz et al. 1998). Bell and Westoby (1986) found that post-settlement movement occurs within seagrass beds, although newly settled fish rarely migrate across bare substrate separating seagrass beds. Post-settlement movements within saltmarshes may be more extensive because fish can travel along a continuous marsh edge, without having to risk exposure by crossing bare areas. As mentioned, *C. nebulosus* and *S. ocellatus* captured from tidal creeks were relatively large (> 15 mm) individuals that may have migrated to the tidal creeks after settlement elsewhere. In contrast to *C. nebulosus* and *S. ocellatus*, newly settled *M. undulatus* at front and rear substations may be the result of 2 temporally separate settlement pulses in these tidal creeks.

Overall densities were relatively similar for all 3 sciaenids between 1997 and 1998. Although no clear trend was evident, densities of *S. ocellatus* and *M. undulatus* tended to be higher at the bay stations (4–6) in 1998. This spatial variation in density may be due to a storm event, which can transport larval fish to areas where fish may not normally reside (Miller 1988). In September 1998, tropical storm Frances created ex-

**Table 5.**

Mean densities (m$^{-2}$ ± 1 SE) for 3 sciaenid species collected from saltmarsh shorelines at 7 stations in West Galveston Bay, Texas, at progressive distances from the tidal pass. Data are from collections made September–November of 1997 and 1998. Sample sizes are given in parentheses in table header.

| Station | *Cynoscion nebulosus* | | *Sciaenops ocellatus* | | *Micropogonias undulatus* | |
| | (96) 1997 | (56) 1998 | (131) 1997 | (239) 1998 | (423) 1997 | (553) 1998 |
|---|---|---|---|---|---|---|
| 1 | 0.00 (0.000) | 0.00 (0.000) | 0.00 (0.000) | 0.32 (0.185) | 0.27 (0.227) | 0.14 (0.099) |
| 2 | 0.02 (0.019) | 0.01 (0.005) | 0.37 (0.223) | 0.11 (0.049) | 0.42 (0.247) | 0.50 (0.161) |
| 3 | 0.02 (0.015) | 0.07 (0.035) | 0.02 (0.008) | 0.06 (0.022) | 0.03 (0.019) | 0.05 (0.034) |
| 4 | 0.13 (0.050) | 0.02 (0.012) | 0.00 (0.000) | 0.12 (0.045) | 0.02 (0.009) | < 0.01 (0.004) |
| 5 | 0.04 (0.022) | 0.06 (0.025) | 0.02 (0.009) | 0.03 (0.010) | 0.00 (0.000) | 0.14 (0.099) |
| 6 | 0.08 (0.045) | 0.02 (0.008) | 0.04 (0.025) | 0.24 (0.122) | 0.02 (0.008) | 0.69 (0.294) |
| 7 | 0.01 (0.002) | 0.01 (0.003) | 0.01 (0.002) | < 0.01 (0.001) | 0.13 (0.056) | 0.08 (0.021) |

tremely high tidal levels during the early *S. ocellatus* recruitment period and may have transported larval *S. ocellatus* to interior bay habitats. The tropical storm occurred before peak recruitment of *M. undulatus*; however, meteorological forcing due to frontal boundaries may have affected larval delivery patterns. Without long-term data though, it is impossible to determine the natural variability in recruitment levels within West Galveston Bay.

This research shows that saltmarsh shorelines in West Galveston Bay serve as nursery areas for commercially important sciaenid species. These species may utilize other habitats (i.e., seagrass) as primary nursery areas (Rooker et al. 1998, Stunz 1999); nevertheless, the impact that marsh habitat has on recruitment processes and ultimately stock structure should not be ignored. Although saltmarsh shorelines may be a secondary nursery habitat for these species, seagrass distribution is limited on the upper Texas coast (Adair et al. 1994) and even at lower densities, saltmarsh shorelines may serve as essential habitat and contribute substantially to adult stocks.

## ACKNOWLEDGMENTS

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# Gulf and Caribbean Research

Gastropod Larvae and Zooplankton in Reef-Related Areas of the Western Caribbean Sea

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# GASTROPOD LARVAE AND ZOOPLANKTON IN REEF-RELATED AREAS OF THE WESTERN CARIBBEAN SEA.

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*ABSTRACT* In order to estimate the composition, distribution and abundance of zooplankton in 3 areas off the western Caribbean, samples were collected in 15 stations at South Coast and Chinchorro Bank, Mexico, and Hol-Chan Belize, from April to December 1996. Duplicate samples (2.5 m³) were collected bimonthly using a submersible pump. The pumped water was filtered through a 202 μm mesh net yielding a total of 20 zooplankton groups. Chinchorro Bank had 19 groups, South Coast had 15 groups, and Hol-Chan had 14 groups. The most abundant groups were copepods (43.1%), fish eggs (29.0%), foraminifera (12.0%), decapod larvae (5.7%) and gastropod larvae (4.3%). Twenty-seven species of gastropod larvae were identified with *Natica* sp. 1, *Rissoina* sp. 1, *Cerithiopsis hero, Cerithium atratum,* and *Epitonium* sp.1 being dominant. Newly hatched veligers of *Strombus gigas* were collected only at Chinchorro Bank (5.7/10m³). Zooplankton was diverse and showed marked changes during the sampling months. Chinchorro Bank had a higher number of marine zooplankters than South Coast and Hol-Chan, and this may be related to a greater oceanic influence. In spite of the environmental homogeneity, there were differences in the distribution and abundance of *Strombus* veligers, and this might be related to some water characteristics locally, affecting gastropod reproduction mainly in South Coast and Hol-Chan.

## INTRODUCTION

Zooplankton communities are dynamic in marine ecosystems. The composition and abundance of reef-related zooplankton differs from those of neritic and oceanic environments, with the difference often being attributed to the shallowness, relatively high temperature, and oligotrophic conditions typical of reef areas (Emery 1968, Sale et al. 1976, Alldredge and King 1977, Alvarez-Cadena et al. 1998). Reef zooplankton are characterized by high diversity and a number of meroplanktonic forms, principally mollusk, decapod, cnidaria and echinodermata larvae (Emery 1968). Some of these are members of the benthos as adults and constitute important fishery resources (Appeldoorn 1994, Stoner and Davis 1997).

In the Mexican Caribbean Sea, zooplankton composition along the northern coast has been investigated. In the bays of this region, copepods, decapod larvae, and fish larvae predominate, with composition varying according to season and habitat heterogeneity (Suárez-Morales et al. 1991, Gasca et al. 1994, Suárez-Morales and Gasca 1996, Alvarez-Cadena et al. 1998, Vásquez-Yeomans 2000). Earlier studies of reef zooplankton in northern Quintana Roo, have indicated a dominance of gammarid amphipods, isopods, mysids, decapod larvae, and fish larvae at night, whereas copepods, siphonophores, chaetognaths, medusae, and salps were dominant during the day (Suárez-Morales and Gasca 1990). In Mahahual, located south of Quintana Roo, copepods and decapod larvae were the most abundant taxa near to

the fore reef, but in the reef lagoon, fish larvae, demersal zooplankton, and other meroplanktonic forms were dominant (Castellanos-Osorio and Suárez-Morales 1997, Vásquez-Yeomans et al. 1998). In spite of this information, the reef area and adjacent zones of the southernmost portion of Quintana Roo such as Chinchorro Bank and South Coast have not been surveyed previously.

The objective of this paper is to describe the reef zooplankton community of the Quintana Roo southern coast, the northern coast of Belize, and to analyze the relationships between these areas. Gastropod larval distribution and abundance in these areas are presented for the first time here.

## MATERIALS AND METHODS

**Study area.** The South Coast (SC) is located along the southern portion of the Yucatan Peninsula, Mexico, and has a mean distance between the shoreline and the barrier reef of about 1 km. The reef lagoon has a mean depth of 3 m and is covered with submerged vegetation. Samples were collected at 4 stations: Hob-Na (18°22′N, 87°47′W), Francesa (18°21′N, 87°47′W), Santa Julia (18°20′N, 87°48′W) and Bacalar Chico (18°11′N, 87°50′W) in May, July, September, and November 1996 (Figure 1).

Chinchorro Bank (CHB) is a false atoll situated in the Mexican exclusive economic zone (18°23′–18°47′N, 87°14′–87°27′W), and is 46 km long, 19 km wide at its widest part, and has an area of 800 km². Its almost elliptic shape shows a strong development of hermatypic coral

growth at the windward zone, whereas at leeward the reef is diffuse and semicontinual. Samples were collected in April, July, September, and November 1996, at 6 stations situated within the reef lagoon: Cayo Lobos (18°23'N, 87°21'W), Isla Che (18°30'N, 87°26'W), Cayo Centro (18°33'N, 87°18'W), Cayo Centro Oeste (18°33'N, 87°24'W), Penelope (18°42'N, 87°14'W), and Cayo Norte (18°45'N, 87°47'W) (Figure 1).

Hol-Chan (HCH) is a marine reserve (11.16 km²) located southwest of Ambergris Key. It is divided into 3shallow zones (1–3 m): Zone A is used for tourism , Zone B is a research area, and Zone C is a species protection area mainly for the queen conch, *Strombus gigas*. Plankton samples were collected in August, October, and December 1996 at 5 stations: Zone A (17°51'N, 87°58'W), Zone B (17°51'N, 87°59'W), Zone C (17°52'N, 87°60'W), North Limit (17°52'N, 87°58'W), and Rocky Point (18°07'N, 87°49'W) (Gibson 1987, Figure1). The reef lagoons at the 3 sites (CHB, SC, HCH)



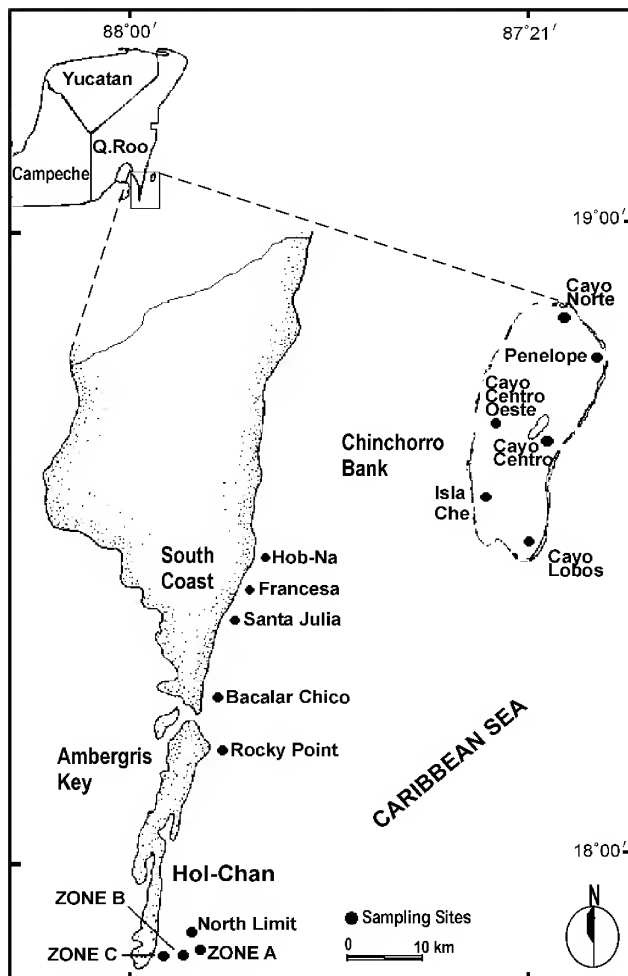**Figure1. Location of sampling stations at Chinchorro Bank, South Coast and Hol-Chan, Southern Caribbean sea.**

have sandy bottoms covered with seagrasses (*Thalassia testudinum, Halodule wrigthii,* and *Syringodium filiforme)* and macro algae (*Laurencia poitei, Dyctiota dichotoma, Penicilus capitatus,* and *Avrainvillea* sp.*).*

Duplicate plankton samples of about 2.5 m³ of seawater were collected using a submersible pump; each sample was filtered through a 202 μm mesh. Samples were fixed in a buffered 5% formalin/sea water solution. Water temperature (°C), salinity (‰) and dissolved oxygen (mg/L) were recorded at each station using either a YSI dissolved oxygen meter or an Ohaus conductivity meter. Samples were taken from the upper 2 m of surface water during the daytime.

Zooplankton were sorted into taxonomic groups using a Zeiss SV-6 stereomicroscope at 50X. Groups were identified with the keys of Boltovskoy (1981) and Raymont (1983). Gastropod larvae were identified following Thiriot-Quievreux (1983), Thiriot-Quievreux and Scheltema (1992), and Davis et al. (1993). All specimens were counted and densities were standardized to number per 10 m³.

Density data for the 6 most abundant zooplankton groups were analyzed with ANOVA methods. Sites and groups were considered as factors and density data were transformed to Ln (x + 1) prior to analysis. Tukey's HSD range test ($P < 0.05$) was employed to find differences among factors (Statgraphics 7.0 Manugistics 1993), if a significant ANOVA was detected.

## RESULTS

The 3 areas were similar in regard to winter temperature, salinity, and dissolved oxygen (Table 1). The taxonomic analysis revealed 20 zooplankton groups; 19 groups occurred at CHB, 15 occurred at SC, and 14 occurred at HCH. At CHB copepods were the most abundant (44.4%) at the 3 sites, followed by fish eggs (31.9%), foraminiferans (8.4%), decapod larvae (7.7%), and gastropod larvae (2.6%). At SC fish larvae were the most abundant group (31.0%); copepods represented 25.5%, followed by foraminiferans (10.4%), and fish eggs (4.7%). At HCH copepods (46.6%), foraminiferans (21.3%), and fish eggs were the most abundant groups. These 6 groups were widely distributed in the study area and represented over (92%) of the total abundance (Table 2).

The highest zooplankton density was recorded at CHB (3625 ± 3687/10m⁻³), followed by HCH (2295.4 ± 2441.95/10m⁻³), and SC (685 ± 975/10m⁻³). At CHB the highest abundance was recorded in September (7565/10m⁻³) and the lowest in July (1519/10m⁻³). At HCH in

**TABLE 1**

**Salinity (‰), water temperature (°C), and dissolved oxygen (DO, mg/l) in Chinchorro Bank (CHB), South coast (SC) and Hol-Chan (HCH) from April to December 1996.**

| Location Date | T °C | Salinity ‰ | DO (mg/l) |
|---|---|---|---|
| **CHB** | | | |
| 24/04/96 | 27.5 | 36.2 | 6.5 |
| 10/07/96 | 28.4 | 36.0 | 6.2 |
| 04/09/96 | 28.5 | 36.0 | 6.3 |
| 4/11/96 | 27.5 | 35.8 | 6.7 |
| Mean | 27.9 | 36.0 | 6.4 |
| SD | 0.55 | 0.16 | 0.22 |
| **SC** | | | |
| 25/05/96 | 28.9 | 36.1 | 6.5 |
| 26/07/96 | 28.6 | 36.3 | 6.8 |
| 28/09/96 | 28.7 | 36.0 | 6.4 |
| 26/11/96 | 28.1 | 35.1 | 6.8 |
| Mean | 28.6 | 35.8 | 6.6 |
| SD | 0.34 | 0.53 | 0.21 |
| **HCH** | | | |
| 13/08/96 | 28.6 | 36.2 | 6.7 |
| 15/10/96 | 27.7 | 35.8 | 6.8 |
| 10/12/96 | 27.0 | 35.7 | 6.8 |
| Mean | 27.8 | 35.9 | 6.8 |
| SD | 0.80 | 0.26 | 0.06 |

October the highest abundance was 4472/10m$^{-3}$ and the lowest occurred in August (292.6/10m$^{-3}$). At SC the highest density values were registered in November (1407/10m$^{-3}$) and minimum in May (205/10m$^{-3}$) (Table 2).

Amphipods, euphausids, ostracods, pteropods, and stomatopods were absent at SC. At HCH apendicularians, amphipods, salps, stomatopods, and echinodermata were not collected, whereas at CHB ostracods were absent (Figure 2). There were no significant differences in densities among species and sites (two-way ANOVA, $F_{2,17} = 1.524$, $P > 0.05$). A total of 27 species of gastropod larvae occurred in the study area. In HCH 21 species were recorded. *Natica* sp. 1, *Rissoina* sp. 1, *Cerithiopsis hero* (Bartsch, 1911), *Cerithium atratum* (Born, 1778), *Epitonium* sp. 1, *Epitonium* sp. 3, and *Atlanta* sp. 1 were the most abundant. Twelve gastropod species were found at CHB. *Natica* sp. 1, *Rissoina* sp. 1, and *Creceis aciculata* were the most abundant. SC had 13 species, with *Natica* sp. 1 and *Mitrella* sp. 1 being the most abundant. Larvae of queen conch (*Strombus gigas* Linnaeus, 1758) occurred only at CHB. One larva of *Strombus raninus* (Gmelin, 1791) was found at SC (Table 3).

Gastropod larvae showed a similar seasonal variation pattern as zooplankton. Pearson correlations showed strong correlation between zooplankton and gastropod larvae densities at CHB ($r^2 = 0.933$) and HCH ($r^2 = 0.950$), whereas in SC an inverse relation was found ($r^2 = 0.265$) (Figure 3).

## DISCUSSION

Apparently there is considerable environmental homogeneity in the Caribbean reefs and this is reflected in the associated zooplankton communities (Moore and Sander 1976, Morales and Murillo 1996). However, seasonal variations may be pronounced, as in the case of the central Great Barrier Reef of Australia (McWilliam et al. 1981, Sammarco and Crenshaw 1984).

The number of zooplankton groups in this study agrees with other studies conducted in the Caribbean, despite the different sampling methods. At Cahuita National Park, Morales and Murillo (1996) using plankton tows, found 17 zooplankton groups, dominated by holoplanktonic forms, and Castellanos-Osorio and Suárez-Morales (1997) described 30 groups from Mahahual, Quintana Roo. Plankton nets and light traps have been shown to collect a similar array of zooplankton elsewhere. For example, in Costa Rica, Morales and Murillo (1996) collected 17 groups in plankton nets while in Australia, Sale et al. (1978) collected 26 groups using light traps. In our study, the pump method was useful for collecting zooplankton in shallow reef patches where standard tows were difficult to operate. It is probable that the difference in zooplankton abundance is more influenced by natural variation rather than the gear type used to collect samples.

Copepods (46%), fish eggs (18%), foraminiferans (21%), gastropod larvae (5%), decapod larvae (1%), and fish larvae (0.33%) were the most abundant groups in our survey. Similarly, Morales and Murillo (1996) reported a predominance of copepods year round (32 to 95%), followed by foraminiferans (1 to 34%), fish larvae and eggs (1 to 28%), and chaetognaths (1 to 6.5%). A similar pattern was observed by Ferraris (1982) at Carrie Bow Cay Belize, where copepods represented 53% of the catch and at Mahahual Quintana Roo where copepods represented 43% of the catch (Castellanos-Osorio and Suárez-Morales 1997).

The relatively higher taxonomic richness and density in CHB might be related to the strong oceanic influence over the bank. Many organisms were holoplanktic (68.4%) and zooplankton density increased because of vertically migrating meroplankton at night

**Table 2**

Zooplankton density (No.10 m⁻³) in Chinchorro Bank (CHB), South Coast (SC) and Hol-Chan (HCH).

| Taxa | CHB | | | | | | SC | | | | | | HCH | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Apr | Jul | Sep | Nov | Mean | SD | May | Jul | Sep | Nov | Mean | SD | Aug | Oct | Dec | Mean | SD |
| Copepods | 264 | 912 | 4561 | 845 | 1645.5 | 1965.32 | 52 | 128 | 519 | 0 | 174.7 | 235.44 | 74 | 2550 | 587 | 1070.3 | 1308.85 |
| Fish eggs | 582 | 89 | 2063 | 1895 | 1157.2 | 972.4 | 0 | 0 | 129 | 0 | 32.5 | 64.50 | 10 | 544 | 766 | 440.0 | 388.58 |
| Foraminiferans | 189 | 118 | 193 | 724 | 306.0 | 280.7 | 85 | 32 | 88 | 80 | 71.2 | 26.37 | 146 | 554 | 766 | 488.7 | 315.12 |
| Decapod larvae | 588 | 237 | 237 | 56 | 279.5 | 222.6 | 14 | 50 | 38 | 359 | 115.2 | 163.19 | 17 | 47 | 17 | 27.0 | 17.32 |
| Gastropod larvae | 30 | 25 | 165 | 150 | 92.5 | 75.3 | 32 | 12 | 28 | 41 | 28.2 | 12.12 | 12 | 284 | 40 | 112.0 | 149.61 |
| Fish larvae | 4 | 5 | 26 | 0 | 8.7 | 11.7 | 0 | 23 | 1 | 825 | 212.2 | 408.64 | 22 | 1 | 0 | 7.7 | 12.42 |
| Chaetognatha | 2 | 55 | 66 | 17 | 35.0 | 30.4 | 0 | 0 | 6 | 12 | 4.5 | 5.74 | 1 | 188 | 1 | 63.3 | 108.0 |
| Apendicularians | 0 | 7 | 152 | 0 | 39.7 | 74.9 | 0 | 0 | 11 | 12 | 5.7 | 6.65 | 0 | 0 | 0 | 0 | 0 |
| Siphonophora | 2 | 1 | 20 | 6 | 7.2 | 8.7 | 0 | 0 | 0 | 40 | 10.0 | 20.00 | 0 | 128 | 0 | 42.7 | 73.90 |
| Bivalves | 0 | 11 | 12 | 0 | 5.7 | 6.6 | 0 | 0 | 12 | 32 | 11.0 | 15.09 | 0 | 98 | 0 | 32.7 | 56.58 |
| Polychaeta | 17 | 8 | 26 | 30 | 20.2 | 9.8 | 3 | 0 | 8 | 3 | 3.5 | 3.31 | 0 | 14 | 0,6 | 4.9 | 7.91 |
| Isopods | 6 | 1 | 13 | 0 | 5.0 | 5.9 | 15 | 20 | 20 | 0 | 13.7 | 9.46 | 10 | 27 | 8 | 15.0 | 10.44 |
| Pteropods | 0.6 | 34 | 19 | 6 | 14.9 | 14.8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 15 | 0 | 5.0 | 8.66 |
| Ostracods | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0,6 | 20 | 0 | 6.9 | 11.37 |
| Amphipods | 2 | 6 | 3 | 7 | 4.5 | 2.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Salps | 2 | 0 | 0 | 0 | 0.5 | 1.0 | 0 | 0 | 5 | 3 | 2.0 | 2.44 | 0 | 0 | 0 | 0 | 0 |
| Euphausiacea | 1 | 0 | 6 | 0 | 1.7 | 2.8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Echinodermata | 0 | 0 | 0.6 | 0 | 0.15 | 0.3 | 4 | 0 | 0 | 0 | 1.0 | 2 | 0 | 0 | 0 | 0 | 0 |
| Nematoda | 0 | 0 | 2 | 0 | 0.5 | 1.0 | 0 | 0 | 1 | 0 | 0.2 | 0.50 | 0 | 2 | 0 | 0.7 | 1.15 |
| Stomatopoda | 0 | 1 | 0 | 0 | 0.25 | 0.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
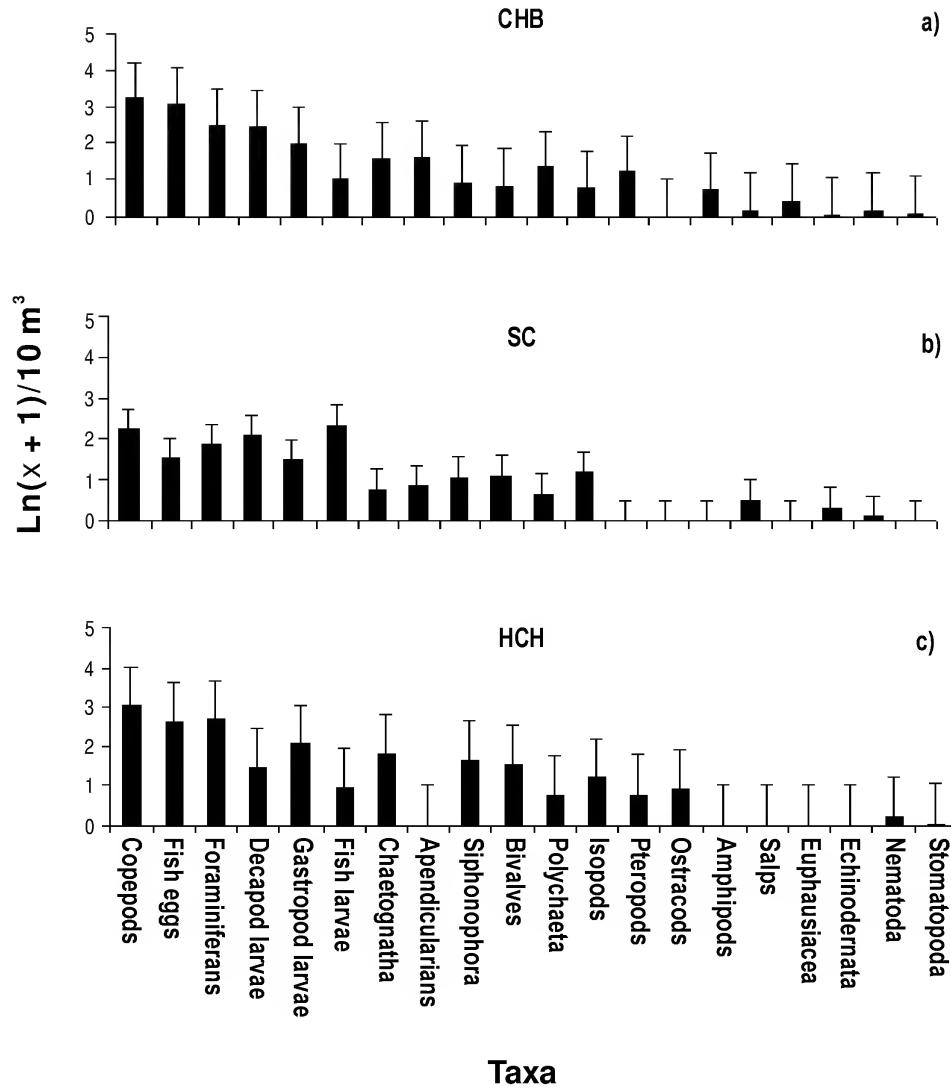
**Figure 2. Zooplankton ($\bar{x}$ ± SD) densities. a = Chinchorro Bank (CHB); b = South Coast (SC); c = Hol-Chan (HCH).**

(Suárez-Morales and Gasca 1990) or by the zooplankton transport by internal bores in the tidal channels (Pineda 1995, Shanks 1998). An increase in the zooplankton densities were observed in rainy and cold seasons (July–October and November–March) within the 3 areas. Glynn (1973) found higher zooplankton densities after a hurricane in Puerto Rico, and Morales and Murillo (1996) recorded increases in zooplankton numbers at the beginning of the rainy season, probably related to increased availability of food.

Ichthyoplankton were abundant both at CHB and HCH but exhibited a low density at SC. It is a well-known fact that some fishes select particular spawning sites within or near the reef for larval retention (Johannes 1978, Lobel 1989, Vázquez-Yeomans 2000).

Gastropod larvae were most abundant in CHB followed by HCH and this could be related to increased

depth and greater oceanic influence in those areas compared to SC. All gastropod larvae found were actaeplanic larvae according to Scheltema's (1989) definition. These larvae spend a maximum of 6 weeks in the water column and primarily are coastal species. Almost all gastropod larvae found here have a small size in the adult stage (3 cm maximum shell length) and species such as *Natica* sp. 1, *Rissoina* sp. 1, and *Epitonium* sp. 1 were widely distributed in the study area. The exceptions were *Strombus raninus* and *S. gigas*, which attain large sizes as adults (7 and 30 cm shell length, respectively) and are commercially exploited in the region. *Strombus raninus* larvae were collected only at SC, whereas *S. gigas* were collected at CHB. No *S. gigas* larvae were collected from HCH, and this could be related to a reproductive failure of *S. gigas* adults in environments near shore, mediated by some environmental component (McCarthy et al.

**Table 3**

**Gastropod larvae abundance (No.10 m$^{-3}$) at Chinchorro Bank (CHB), South Coast (SC) and Hol-Chan (HCH).**

| Species | CHB Apr 23/96 | Jul 11/96 | Sep 4/96 | Nov 28/96 | Mean | SD | SC May 23/96 | Jul 26/96 | Sep 25/96 | Nov 25/96 | Mean | SD | HCH Aug 13/96 | Oct 15/96 | Dec 10/96 | Mean | SD |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Natica* sp. 1 | 1 | 1.4 | 17.0 | 19.0 | 9.6 | 9.74 | 5.0 | 2.5 | 1.2 | 1.2 | 2.5 | 1.79 | 0.8 | 0 | 17.5 | 6.1 | 9.88 |
| *Natica* sp. 2 | 0 | 0.7 | 0.7 | 3.5 | 1.3 | 1.55 | 0 | 0 | 1.2 | 0 | 0.3 | 0.6 | 0 | 0 | 0 | 0 | 0 |
| *Natica* sp. 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3.3 | 1.1 | 1.91 |
| *Rissoina* sp. 1 | 2.1 | 2.8 | 6.4 | 0 | 2.8 | 2.66 | 22.5 | 5.0 | 0 | 2.5 | 7.5 | 10.21 | 0 | 6.6 | 0.5 | 2.4 | 3.67 |
| *Rissoina* sp. 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2.5 | 0.6 | 1.25 | 0 | 25.0 | 0.5 | 8.5 | 14.29 |
| *Mitrella* sp. 1 | 0 | 0.7 | 0 | 2.1 | 0.7 | 0.99 | 7.5 | 0 | 0 | 1.2 | 2.2 | 3.59 | 1.6 | 2.5 | 1.6 | 1.9 | 0.52 |
| *Mitrella* sp. 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5.0 | 0 | 1.6 | 2.88 |
| *Cerithiopsis hero* | 0 | 0 | 9.2 | 0 | 2.3 | 4.60 | 0 | 0 | 0 | 0 | 0 | 0 | 0.8 | 2.5 | 2.5 | 1.9 | 0.98 |
| *Cerithiopsis* sp. 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3.3 | 0.8 | 1.4 | 1.72 |
| *Cerithiopsis* sp. 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *Cerithium atratum* | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.2 | 0.3 | 0.60 | 0 | 23.3 | 0 | 7.7 | 13.45 |
| *Alaba* sp. | 0 | 0 | 0 | 0.7 | 0.2 | 0.35 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 35.8 | 4.1 | 13.3 | 19.59 |
| *Epitonium* sp. 1 | 0 | 0 | 2.5 | 0 | 0.6 | 1.25 | 0 | 0 | 0 | 1.5 | 0.4 | 0.75 | 0 | 25.0 | 1.6 | 8.9 | 13.99 |
| *Epitonium* sp. 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2.5 | 0.6 | 1.25 | 0 | 4.1 | 0 | 1.4 | 2.37 |
| *Epitonium* sp. 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 11.6 | 0 | 3.9 | 6.70 |
| *Simnia acicularis* | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.8 | 0 | 0.3 | 0.46 |
| *Aporrhais* sp. | 0 | 0.7 | 0 | 0 | 0.2 | 0.35 | 1.2 | 0 | 0 | 0 | 0.3 | 0.60 | 0 | 0 | 0 | 0 | 0 |
| *Creseis acicula* | 0 | 2.1 | 6.4 | 2.8 | 2.8 | 2.66 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5.8 | 0 | 1.9 | 3.35 |
| *Strombus gigas* | 0 | 5.7 | 0 | 0 | 1.4 | 2.85 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *Strombus raninus* | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.2 | 0 | 0.3 | 0.60 | 0 | 0 | 0 | 0 | 0 |
| *Seila* sp. | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.2 | 0.3 | 0.60 | 0 | 0 | 0 | 0 | 0 |
| *Bittium* sp. | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5.8 | 0 | 1.9 | 3.35 |
| *Lunatia* sp. | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.8 | 0.3 | 0.46 |
| *Atlanta* sp. | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 10.0 | 0 | 3.3 | 5.77 |
| *Limacina* sp. 1 | 0.7 | 0 | 2.1 | 7.1 | 2.5 | 3.21 | 0 | 0 | 0 | 1.4 | 0.4 | 0.70 | 0 | 3.3 | 0.8 | 1.4 | 1.72 |
| *Limacina* sp. 2 | 0 | 0 | 5.7 | 0 | 1.4 | 2.85 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.8 | 0.3 | 0.46 |
| *Limacina* sp. 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3.3 | 0.8 | 1.65 | 0 | 80.8 | 4.1 | 28.3 | 45.51 |
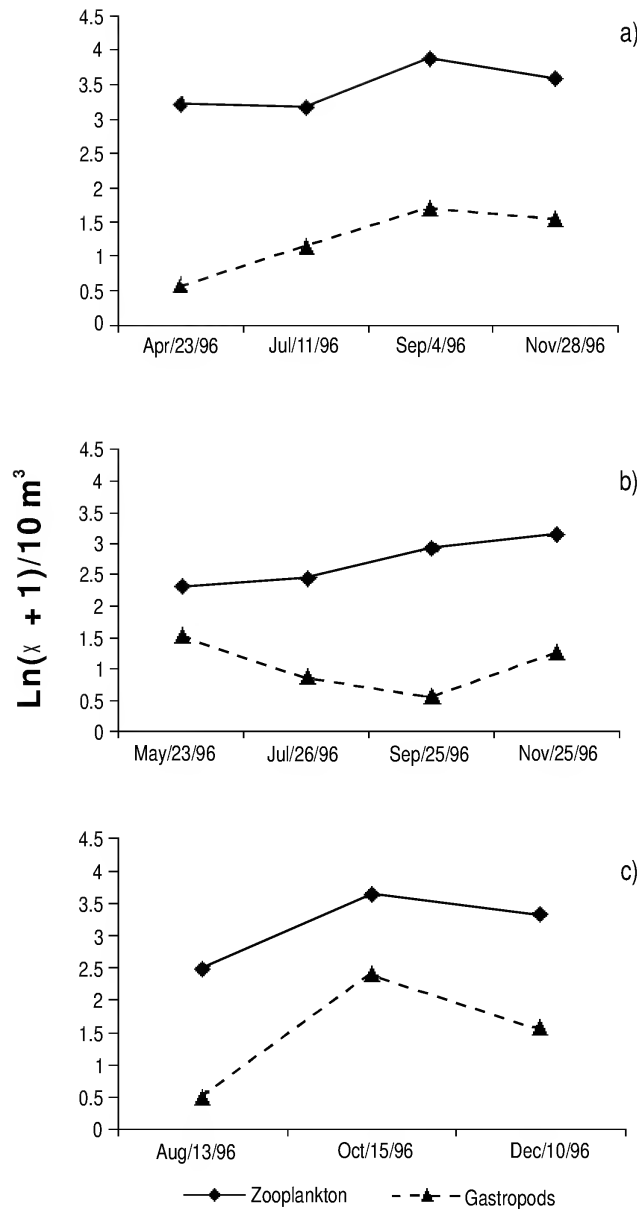
Figure 3. Mean zooplankton and gastropod density variation over time. a = CHB; b = SC; c = HCH.

1999), as has been reported in Florida.

In the region, several species of *Natica* (5), *Rissoina* (7) (Vokes and Vokes, 1983), *Mitrella* (5), *Cerithiopsis* (5), and *Epitonium* (13) have been reported, but there is currently no available information on their larval stages; many of them are reported here for first time. In July, newly hatched veligers of *S. gigas* (5.7/10m$^{-3}$) were collected at CHB. This value is higher than the 1.2 larvae/10m$^{-3}$ reported from Florida (Stoner et al. 1997) and similar to the density found in the Bahamas (4.5/ 10m$^{-3}$, Stoner and Davis 1997). Apparently, CHB is an important site for production of *S. gigas* veligers (Stoner et al. 1997). Samples collected with plankton tows at

CHB showed that the reproductive period of strombids is from February to November with a peak in August and October (de Jesús-Navarrete and Aldana-Aranda 2000). Hence, the higher density of gastropods found in the rainy and cold season may be related to the spawning season. In spite of the environmental homogeneity, there were differences in the distribution and abundance of *Strombus* veligers, and this might be related to some water characteristics locally, affecting gastropod reproduction mainly in SC and HCH.

## ACKNOWLEDGMENTS

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# Gulf and Caribbean Research

January 2001

The Chaetognatha of the Southwestern Gulf of Mexico During April-May, 1986

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# THE CHAETOGNATHA OF THE SOUTHWESTERN GULF OF MEXICO DURING APRIL–MAY, 1986

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*ABSTRACT* An analysis of the distribution and abundance of Chaetognatha species from the Gulf of Mexico during April–May 1986 is presented. Zooplankton samples were collected at 43 stations from the southwestern and eastern regions of Mexico's Exclusive Economic Zone in the Gulf of Mexico. Species richness and abundance were higher in the southwestern stations located at the platform slope. The rank of Importance Value (IV) shows 3 groups of species; the first group included *Flaccisagitta enflata, Mesosagitta minima, Serratosagitta serratodentata, Krohnitta subtilis, Pterosagitta draco, Sagitta bipunctata,* and *Krohnitta pacifica* which were the most widely distributed species during this period. Density data were classified and analyzed by Morisita's similarity index, depicting 2 large groups of sampling stations along with a third group made up of 5 stations. Two stations were distinct from the others because of the low species richness and because only 2 species with high densities were present. Simpson's dominance index showed low values throughout the study area. Densities of chaetognath species did not differ significantly between day and night samples.

## INTRODUCTION

Studies on Chaetognatha are relevant given their importance as predators of zooplankton, including copepods and fish larvae, and also for their role as indicators of particular hydrological conditions of water masses in the oceans (Alvariño 1965, McLelland 1989). Among the studies that focus on chaetognaths in the Gulf of Mexico we highlight those of Owre (1960) and Pierce and Was (1962) in the Florida Current; Pierce (1962) off the coast of Texas; McLelland (1989) in the Mississippi vicinity; and Every (1968) and McLelland and Perry (1989) in the northeastern oceanic zone of the Gulf. There have been studies in Mexico's Economic Exclusive Zone (EEZ), and these have been conducted in local regions: Vega-Rodríguez (1965) off the coast of Veracruz; Rivero-Beltrán (1975) in the Campeche Sound; and Mille-Pagaza et al. (1997) near the Yucatan platform. Since 1986 several oceanographic cruises were conducted in Mexico's EEZ, which comprises the oceanic southern, eastern, and western regions of the Gulf of Mexico in a wide network of stations. Among other results, the distribution of chaetognath species from the southeastern zone of the EEZ has been published by Mille-Pagaza and Carrillo-Laguna (1999). The specific composition, density, and distribution of Chaetognatha is presented herein for the basin and the southern and western regions of the Gulf of Mexico during April–May 1986.

## MATERIALS AND METHODS

Samples were collected by the Instituto National de Pesca in April and May 1986 aboard the R/V *Justo Sierra* oceanographic ship (Cruise JS-8601) at 43 sampling stations in the basin, the southern, and western areas of Mexico's EEZ in the Gulf of Mexico (Figure 1). Zooplankton were sampled day and night by oblique tows at depths from 10 to 200 m using a bongo-type net (250 µm mesh). Chaetognaths (9,478) were removed from 10% aliquots for enumeration and identification using the keys and descriptions of McLelland (1989).

Species richness and abundance were calculated as orgs./100 m³. The Importance Value (IV) (Krebs 1994) and Simpson's dominance Index (Stiling 1999) were obtained using relative abundances and frequencies of the species collected. Similarity between stations was estimated using Morisita's Index (Krebs 1989) and the corresponding dendrogram was derived using the unweighted average procedure (UPGMA). The Mann-Whitney U-test ($\alpha = 0.05$) was used to compare differences between day and night densities of each chaetognath species (Collins and Stender 1989, Zar 1999). A discriminant analysis was performed using surface (10 m) temperature, salinity, dissolved oxygen, and the cluster analysis results to detect which environmental factors influenced chaetognath community composition and density distribution. The relative importance of discriminating variables was judged by the absolute value of standardized coefficients of function. Chi squared ($\alpha = 0.05$) was used as the test statistic (Chester and Thayer 1990, Morrison 1990).
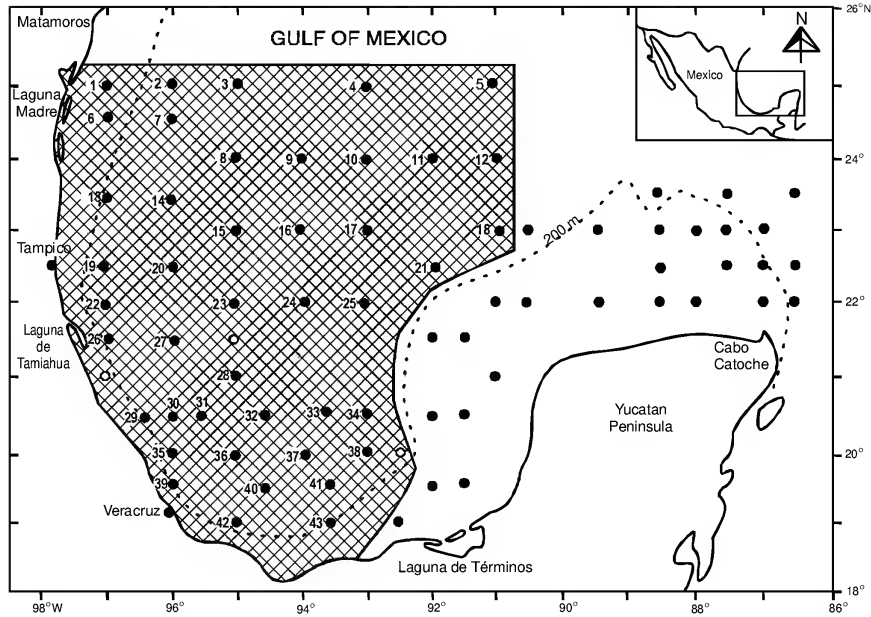
Figure 1. Study area. The hatched area indicates the region of the Gulf of Mexico analyzed in the present study.

## RESULTS AND DISCUSSION

A total of 14 Chaetognath species were found ranging from 7 to 12 species per station, although most stations usually had 9 to 10 species. The lowest species numbers occurred in the southern and oceanic regions (Figure 2). There was a tendancy toward increasing species richness at stations near the platform or slope, which is similar to the pattern found at the Campeche Bank (Mille-Pagaza et al. 1997, Mille-Pagaza and Carrillo-Laguna 1999). Species richness in the neritic

zone may be attributed to river run-off promoting increases in phytoplankton in coastal areas and thus chaetognath abundance (Alvariño 1965).

The area of highest total density (3,699 orgs./100 m$^3$) was found at a station close to the coast in the northwestern portion of the study area and consisted mainly of the species *Flaccisagitta enflata* (Grassi, 1881) and *Sagitta tenuis* Conant, 1896 (Figure 3). However, the lowest species number was also recorded at this station. High densities of between 1,101 and 2,980 orgs./100 m$^3$ were present at several stations in the western and southern
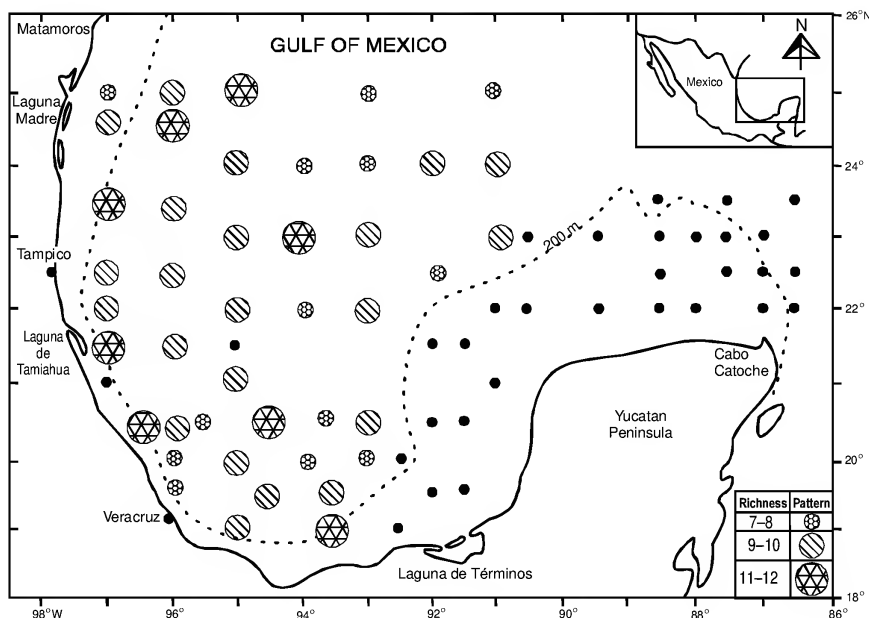


Figure 2. Species richness (number) distribution of chaetognaths in the Gulf of Mexico study area.
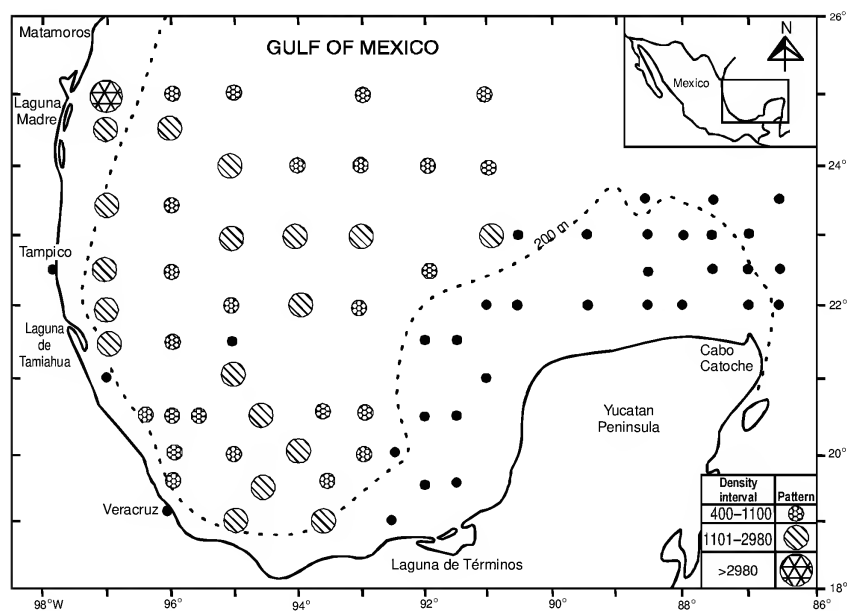
**Figure 3. Density distribution of chaetognaths (orgs./100 m³) in the Gulf of Mexico study area. The scale of the interval is in *e* base.**

regions and in the basin where numbers greater than 2,000 orgs./100 m³ were recorded. In most of the study area, however, abundances ranged from 400 to 1,100 orgs./100 m³. In the vicinity of a small upwelling zone (Belousov et al. 1966), off the coast of Veracruz (Station 30), less than 500 orgs./100 m³ were collected. During the present study, Chaetognath density generally was lowest in the southwestern Gulf of Mexico. Values between 1,000 and 5,000 orgs./100 m³ were recorded at the Campeche Bank during this same period (Mille-Pagaza and Carrillo-Laguna 1999), with peak densities in the Campeche Sound exceeding 5,000 orgs./100 m³. This confirms the high productivity that has been reported for the area (Bessonov et al. 1971).

Chaetognath species with the lowest densities (< 50 orgs./100 m³), in decreasing order were: *S. tenuis*, present in the eastern portion of the study area and the most northern station, where found in numbers over 1,000 orgs./100 m³; *Flaccisagitta lyra* (Krohn, 1853), was found dispersed throughout the area; *Mesosagitta decipiens* (Fowler, 1905) and *Ferosagitta hispida* (Conant, 1895), were found in similar areas at the western and southern stations (the latter also reached a moderate density of 436 orgs./100 m³ at Station 1); *Mesosagitta sibogae* (Fowler, 1906) was only present at 4 stations in the basin in very low densities; and *Sagitta friderici* Ritter-Zahony, 1911 was collected only at one station in the basin and at another close to the slope off the Tabasco state coast.

Species with the highest abundances were *F. enflata* and *Mesosagitta minima* (Grassi, 1881), both widely distributed in the study area. *Flaccisagitta enflata* was collected in high densities of over 1,000 orgs./100 m³ at stations near the platform in the western Gulf, but was low in abundance (from 200 to 1,000) in other areas. *Mesosagitta minima* was found in numbers over 200 orgs./100 m³ in most areas, but at some stations only reached 500 and 1,000 organisms.

Other species distributed throughout the study area included: *Krohnitta pacifica* (Aida, 1897), *K. subtilis* (Grassi, 1881), *Sagitta bipunctata* Quoy and Gaimard, 1827, and *Flaccisagitta hexaptera* (d'Orbigny, 1843). In general, numbers for these species ranged from 4 to 50 orgs./100 m³, but reached over 200 orgs./100 m³ at some stations. *Serratosagitta serratodentata* (Krohn, 1853) and *Pterosagitta draco* (Krohn, 1853) were found throughout the study area, with densities between 100 and 500 orgs./100 m³ in the oceanic zone, but lower densities were seen nearer the platform and slope. This coincides with Owre's (1960) finding for the Florida Current.

Results of the Importance Value (IV) analysis indicated 3 species sets (Table 1). The first set (IV > 10), was headed by *F. enflata* and *M. minima*, followed by *S. serratodentata, K. subtilis, P. draco, S. bipunctata,* and *K. pacifica*. The species *S. tenuis, F. hexaptera, F. hispida,* and *M. decipiens* were grouped together in the 2nd set (IV = 5–10). Finally, *F. lyra, M. sibogae* and *S. friderici* made-up the 3rd set (IV < 5).

## TABLE 1

**Species Importance Value (IV) of chaetognaths found in the Gulf of Mexico study area during April–May 1986, and their worldwide distribution. *Species reported for the Gulf of Mexico by McLelland 1989.**

| Species | IV | Worldwide Distribution (Alvariño 1965, 1969) |
|---|---|---|
| Set 1 | | |
| *Flaccisagitta enflata* | 52.78 | Oceanic, epiplanktonic, temperate-tropical. |
| *Mesosagitta minima* | 32.09 | Oceanic, epiplanktonic, tropical-temperate. |
| *Serratosagitta serratodentata* | 19.45 | Oceanic, epiplanktonic, Atlantic-temperate, tropical |
| *Krohnitta subtilis* | 16.34 | Oceanic, epiplanktonic, temperate, tropical |
| *Pterosagitta draco* | 15.76 | Oceanic, epiplanktonic, tropical-temperate |
| *Sagitta bipunctata* | 14.92 | Oceanic, epiplanktonic, tropical-temperate |
| *Krohnitta pacifica* | 11.88 | Oceanic, epiplanktonic, tropical-ecuatorial |
| Set 2 | | |
| *Sagitta tenuis* | 9.49 | Neritic, epiplanktonic, Atlantic-tropical-ecuatorial |
| *Flaccisagitta hexaptera* | 9.27 | Oceanic, epiplanktonic, tropical-temperate |
| *Ferosagitta hispida* | 7.22 | Oceanic, epiplanktonic, Atlantic-tropical-ecuatorial |
| *Mesosagitta decipiens* | 5.55 | Oceanic, epimesoplanktonic, tropical-temperate |
| Set 3 | | |
| *Flaccisagitta lyra* | 3.27 | Oceanic, epiplanktonic, tropical-temperate |
| *Mesosagitta sibogae* | 1.36 | Oceanic, mesoplanktonic, temperate |
| *Sagitta friderici* | 0.61 | Neritic, epiplanktonic, Atlantic-tropical-ecuatorial |

The species in the first set, with the exception of *K. pacifica*, were distributed over 90% of the study area. However, some species were present in had very low abundances in some areas which is indicative of their oceanic or neritic nature. The position of *F. enflata* corresponds to that reported for the Campeche Bank (Mille-Pagaza et al. 1997, Mille-Pagaza and Carrillo-Laguna 1999) and agrees with the cosmopolitan species category assigned by several authors (Alvariño 1965, 1969, Michel 1984, McLelland 1989). On the other hand, some species showed inconsistent distribution patterns (e.g., *M. minima*). Owre (1960) indicated that
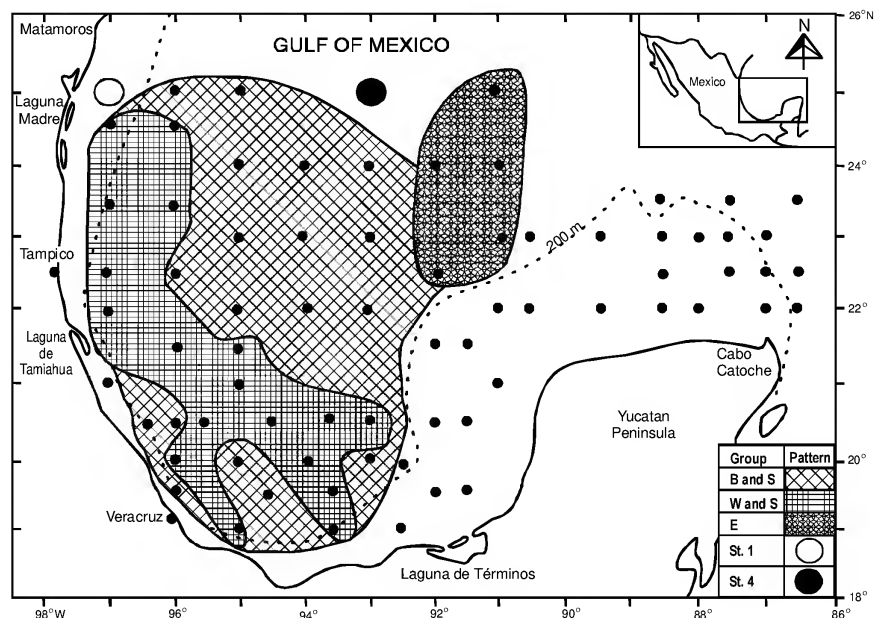


**Figure 5. Spatial distribution of the groups obtained with Morisita's similarity index. Basin and South (B and S) West and South (W and S), East (E) and station (St.).**

54

this species was a coastal species found in low abundances in the oceanic zone and was a species characteristic of mixed waters. Alvarino (1968) indicated that it was scarce in the Gulf of Mexico. In this study, *M. minima* it was found distributed throughout the entire area, with moderate to high abundances. Its distribution could be indicative of mixed surface waters from the Gulf stream and coastal waters (Vazquez de la Cerda 1975).

*Ferosagitta hispida* (2nd set) is considered to be a neritic form by Alvariño (1965) and McLelland (1989) and a possible indicator species of waters from the Gulf of Mexico (Pierce 1951, Owre 1960). In this study, it was restricted to the neritic zone but did occur in some oceanic stations. *Sagitta tenuis,* also a neritic species (Alvariño 1965, McLelland 1989), showed a similar distribution to that of *F. hispida. Mesosagitta decipiens*, a mesoplanktonic species, was present over the slope, which may be indicative of a mixture of deep and surface waters given the active hydrodynamics of the Gulf of Mexico (Vazquez de la Cerda 1975, Gasca 1999). This species was also recorded with a low IV value in the Campeche Bank by Mille-Pagaza and Carrillo-Laguna (1999).

Densities of chaetognath species did not differ significantly between night and daytime samplings, reflecting that most of the species collected are cosmopolitan, epiplanktonic, and are broadly distributed in the tropical and subtropical waters of the study area (Alvariño 1969, Michel 1984). This result agrees with those obtained for siphonophores in the Gulf of Mexico southwestern zone (Gasca 1999); however, Collins and Stender (1989) did find differences for mugilids larvae between day and night catches in the southwestern US.

Simpson's dominance index ranged from 0.14 to 0.54. In general, the highest values (> 0.30) were found close to the slope of the western platform and towards the southern zone of the study area. The highest dominance value (0.54) was recorded at Station 41 where *F. enflata* dominated. The lowest dominance values were recorded at the center of the basin where there were no predominant species. This pattern could be attributed to low abundances of chaetognath species as a result of the oligotrophic waters (Gasca 1997).

From the dendrogram constructed, 3 groups of sampling stations and 2 individual stations were defined when an arbitrary break was set at 0.87 (Figure 4). The first large group of 19, were basin and Gulf stations, where several species with relatively high and others with very low densities were collected (Figure 5). No clear dominance was established by any species, which was confirmed by the Simpson's index values (0.14 to 0.29). *Flaccisagitta enflata* and *M. minima* were the dominant species in the 2nd group of 17 stations located
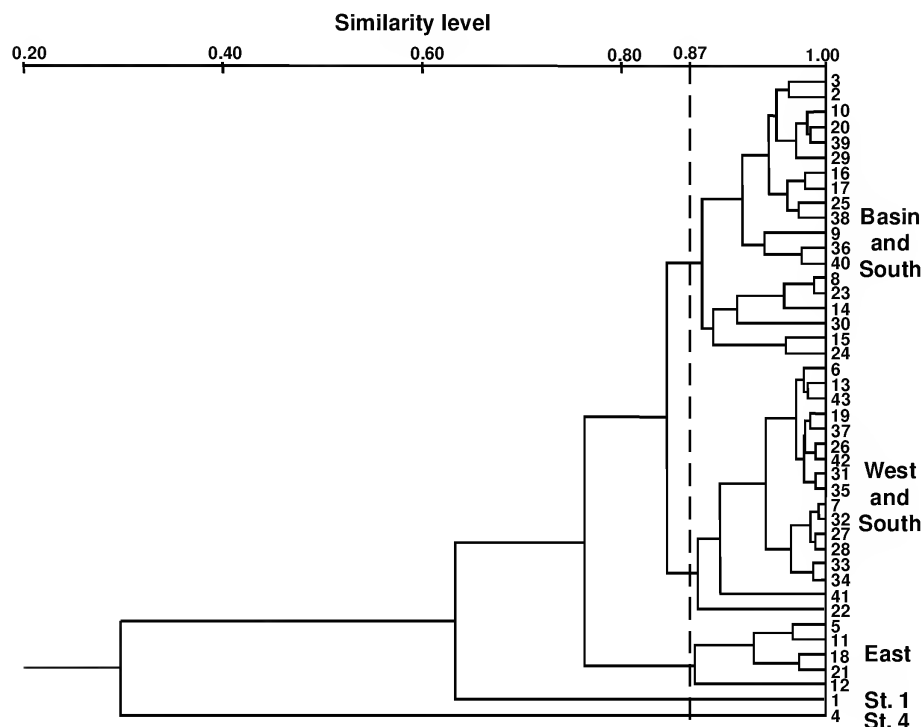


Figure 4. Dendrogram obtained with Morisita's similarity index and UPGMA's grouping method.
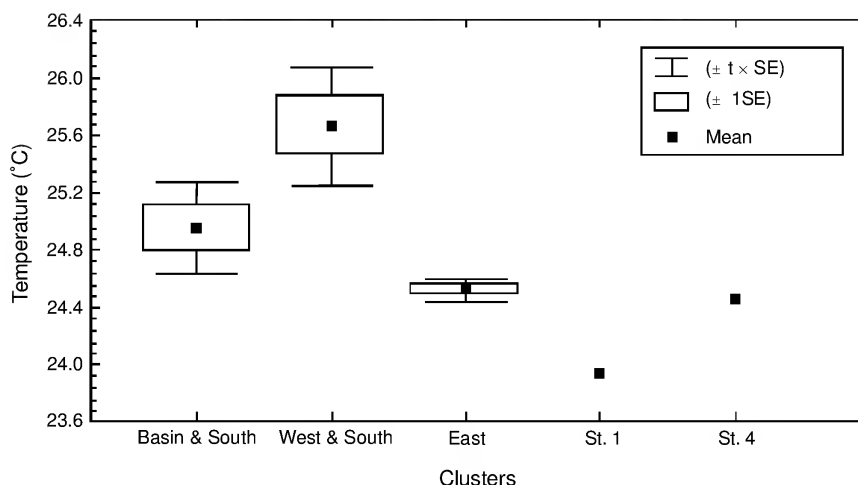
**Figure 6. Boxplots of water temperature for each cluster obtained with Morisita's similarity index. t = value from t-distribution table.**

in the southern zone and western slope region. The highest dominence index values for this group of stations ranged between 0.30 and 0.54 (Figure 5).

Five stations located in the eastern portion of the study area made-up the 3rd group (Figure 5). The densities of species in this group varied widely with no detectable trend. This group of stations also showed low dominance index values of between 0.16 and 0.26.

Stations 1 and 4 were separated from the other 3 groups by a similarity level value of less than 0.65. In these 2 stations (Figure 5) only 8 and 7 species, respectively, were present. Most species were represented by very low numbers with only 2 species at higher densities. *Sagitta tenuis* and *F. enflata* were found at Station 1 with over 1000 orgs./100 m$^3$. At Station 4, *M. decipiens* and *M. minima* ranged between 201 and 500 orgs./100 m$^3$ while *M. sibogae* reached a maximum density of only 30 orgs./100 m$^3$.

Multiple discriminant analysis applied to abiotic variables showed that species densities and chaetognath community composition were influenced primarily by temperature (Figure 6). The other variables did not differ significantly among station clusters ($P = 0.05$). Gasca (1999) found similar results for siphonophores; moreover, Alvariño (1969) asserted that food resources were a fundamental factor in chaetognath species distribution in other Atlantic regions. More investigation must be done in order to demonstrate the relationship between chaetognath abundance and environmental variables.

### ACKNOWLEDGMENTS

We wish to thank M.E. Sánchez-Salazar for her assistance in the translation of this manuscript. We thank anonymous reviewers for their valuable constructive comments and suggestions.

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Tanaidacea (Crustacea: Peracardia) of the Gulf of Mexico. IX. Geographical Occurrence of *Apseudes olimpiae* Gutu, 1986 with a Review of Previous Records for the Genus Apseudes in the Gulf

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# TANAIDACEA (CRUSTACEA: PERACARIDA) OF THE GULF OF MEXICO. IX. GEOGRAPHICAL OCCURRENCE OF *APSEUDES OLIMPIAE* GUȚU, 1986 WITH A REVIEW OF PREVIOUS RECORDS FOR THE GENUS *APSEUDES* IN THE GULF

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*Abstract* Examination of tanaidacean specimens collected from shelf waters of the eastern Gulf of Mexico (Gulf) revealed the presence of the apseudomorph *Apseudes olimpiae* Guțu, 1986, whose type locality was unknown, but suspected to be Bermuda. It is now determined that the type material actually came from the northeastern Gulf. Although the specific station locality information for the type material has been lost; records indicate that specimens from the Gulf were sent to Romania for study by M. Băcescu and apparently became mixed with material from Bermuda. Based on additional material from the present study, new locality records are established for *A. olimpiae* in shelf waters (19–47 m) off the coasts of Alabama and northwestern Florida. The original illustrations of Guțu (1986) are reproduced to facilitate the identification of *A. olimpiae* and a map of its known distribution is provided. A brief review of previous records for the genus *Apseudes* Leach, 1814 indicates that *A. olimpiae* is currently the only described species of the genus *sensu stricto* known with certainty from Gulf waters. The taxonomic status for Gulf specimens of another species in the *A. intermedius-bermudeus* complex and the "*Apseudes* sp. A" of Flint and Holland (1980) remain unresolved.

## INTRODUCTION

This report is the 9th in a series of publications on the Tanaidacea of the Gulf (Ogle et al. 1982, Sieg et al. 1982, Sieg and Heard 1983a,b, 1985, 1988, 1989, Meyer and Heard 1989, and Viskcup and Heard 1989). Examination of benthic samples collected in the eastern Gulf during projects sponsored by the Bureau of Land Management (BLM) MAFLA program, US Environmental Protection Agency (EPA), and Chevron USA Production Company, revealed the presence of the apseudomorph tanaidacean *Apseudes olimpiae* Guțu, 1986; sampling stations are presented in Figure 1. The type locality for this species was unknown, but was originally suspected to be the Bermuda Islands (Guțu 1986). The purpose of this report is to correct and provide new information on the geographic distribution for *A. olimpiae*.

## RESULTS

**Order Tanaidacea**
**Suborder Apseudomorpha Sieg, 1980**
**Family Apseudidae Leach, 1814**
*Apseudes olimpiae* **Guțu, 1986**
**Figures 2–4**

**Material.** BLM-MAFLA (1974–1978)—1 spec., Station 2421, 29°37'00.8"N, 84°17'00.2"W, June 1976, 19 m

June 1975.—1 spec., Station 2422, 29°29'55.4"N, 84°27'01.4"W, June 1975, 24 m.—6 spec., Station 2423, 29°20'00.4"N, 84°44'02.3"W, 1975, 30 m;—9 spec., Station 2423, September 1977.—6 spec., Station 2424, 29°13'00.7"N, 85°00'01.4"W, 8 June 1975, 28 m.—3 spec. (1 GCRL 2016, 2 USNM-310679), Station 2424, August 1977.—2 spec., Station 2529(34), 29°55'59.0"N, 86°06'28.8"W, July 1976, 39 m.—1 spec., Station 2554, 29°24'00.1"N, 85°42'02.0"W, September 1977, 42 m.—21 spec. (5 GCRL 2015, 6 USNM-310680–310684), Station 39, 29°45'27"N, 86°00'51"W, 6 April 1974, 37 m.—8 spec., Station 40, 29°40'29"N, 86°00'49"W, 4 September 1974, 37 m.—2 spec., Station 50, 28°19'00"N, 84°20'58"W, 15 June 1974, 47 m.—2 spec., Station 62 [off Tampa], 27°50'01"N, 83°30'59"W, 17 June 1974, 34 m.

Chevron Production Company— 3 spec., Station 14, 29°59'23.33"N, 87°29'10.17"W, 25 June 1992, 27 m.—10 spec., Station 15, 30°00'27.16"N, 87°33'17.03"W, 25 June 1992, 29 m.—42 spec., Station 17, 20°02'34.94"N, 87°41'30.91"W, 25 June 1992, 25m.

EPA—1 spec., Station 2, 30°08.91'N, 87°18.05'W, 25 October 1990, 23 m.—1 spec., Station 3, 30°09.00'N, 87°16.99'W, October 1990, 23m.—1 spec., Station 5, 30°06.50'N, 87°17.94'W, 22 October 1990, 25m.

**Diagnosis.** Body robust, calcified; length about 5–6 mm. Carapace, including acute rostrum, equal with first 2 free pereonites. Pereonites 3–6 with anteriorly directed
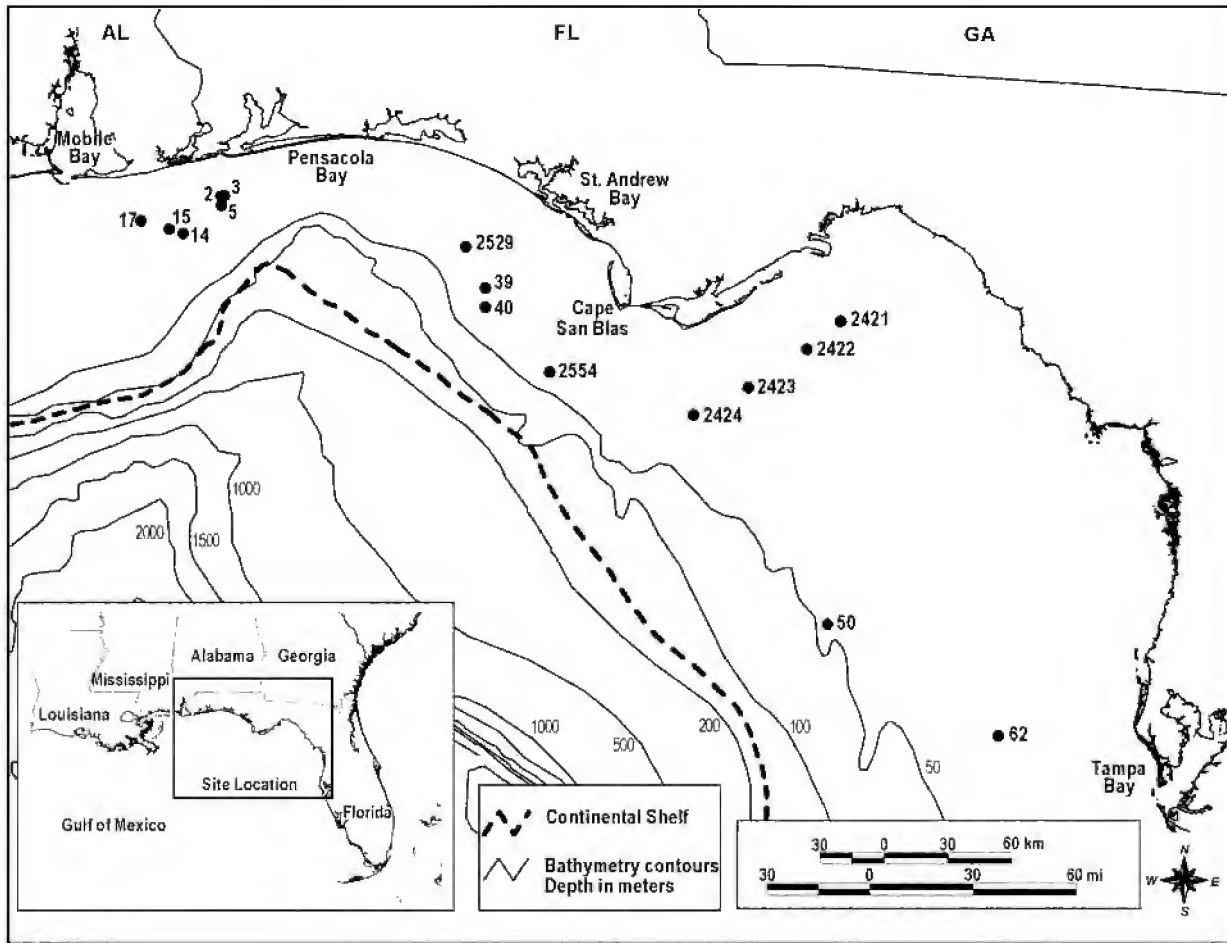
**Figure 1. Map of the northeastern Gulf of Mexico indicating station locations where *Apseudes olimpiae* Guṭu, 1986 occurred and known specific distribution of *A. olimpiae*.**

hook-like lateral spiniform prolongation (Figure 2A). Pereon and pleon with mid-ventral recurved spinous processes on all segments (Figure 2B). Cheliped and pereopod 2 with exopodite (Figure 3C,D and 4A). Pereopods 3–7 relatively cylindrical, slender, with a few long setae, and 0–3 spines on the sternal edges of merus, carpus and propodus (Figure 4B–F). Pleopods, 5 biramous pairs. Chelipeds, sexually dimorphic, males having a carpus with bilobate sternal expansion, a very large propodus, and a tooth on fixed finger and dactyl (Figure 3D).

## REMARKS AND DISCUSSION

Based on our examination of 138 specimens of *A. olimpiae* from the NE Gulf, new locality records are established for the species in shelf waters (19–47 m) from off Tampa Bay, Florida, northwestwards to off Mobile, Alabama. The collection data indicate that *A. olimpiae* appears to prefer sand substrata and may be confined zoogeographically to shelf habitats of the northeastern Gulf (Figure 1). Although we have examined

many collections of apseudomorph tanaidaceans from other parts of the Gulf and adjacent regions, *A. olimpiae* has not been found in any of them.

*Apseudes olimpiae* is immediately distinguished from other shallow water Gulf apseudomorphs by having pereonites 3–6 distinctly bilobed with the 2 anterior lobes armed with an anterolateral hook-like spinose process (Figure 2A). The illustrations (Figures 2–4) from Guṭu (1986) are included to illustrate the characters of *A. olimpae* and to facilitate its identification in Gulf waters.

We believe that Bermuda, the type locality originally postulated for *A. olimpiae* by Guṭu (1986), was incorrect. Based on circumstantial evidence, the type series may have actually come from the eastern Gulf (off Tampa?) and may have been collected in 1977 during an extensive benthic baseline study sponsored by the BLM. Although the specific information on the station locality for the type material was lost, our records indicate that during 1978 apseudomorph specimens were sent with 2 species of cumaceans (later described as *Campylaspis*
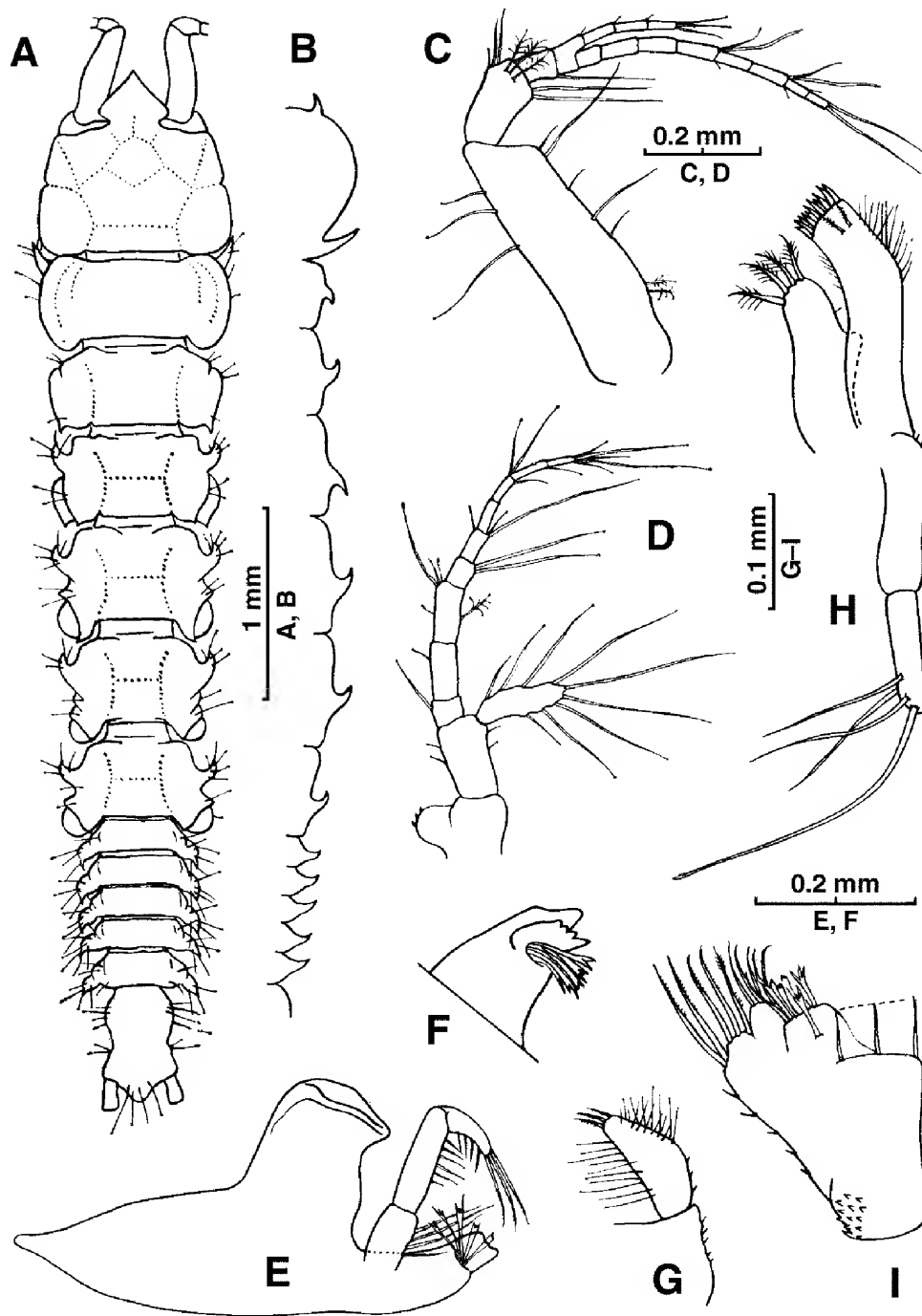
**Figure 2.** *Apseudes olimpiae* Guţu, **1986. Female: A, body dorsal view; B, lateral aspect of body, showing mid-ventral spinous processes; C, antennule; D, antenna; E, right mandible; F, distal end of left mandible; G, labium; H, maxillule; I, maxilla.**

*heardi* Muradian, 1979 and *Heteroleucon heardi* Băcescu, 1979) from the laboratory of R. Heard to M. Băcescu in Romania. These type specimens of *A. olimpiae* were apparently misplaced and became mixed with material from Bermuda, which was being studied by the late M. Băcescu. After careful examination of the tanaidacean holdings in Muséum d'Histoire naturelle "Grigore Antipa, Guţu (personal communication, July 2000) discovered a

vial with fragments of *A. olimpiae* accompanied by a small label with "Tampa" written on it. Whether or not these fragments are part of the BLM material that was collected offshore from Tampa (e.g., Station 62) could not be determined with certainty, but the label does add further circumstantial evidence that the type material came from the eastern Gulf.
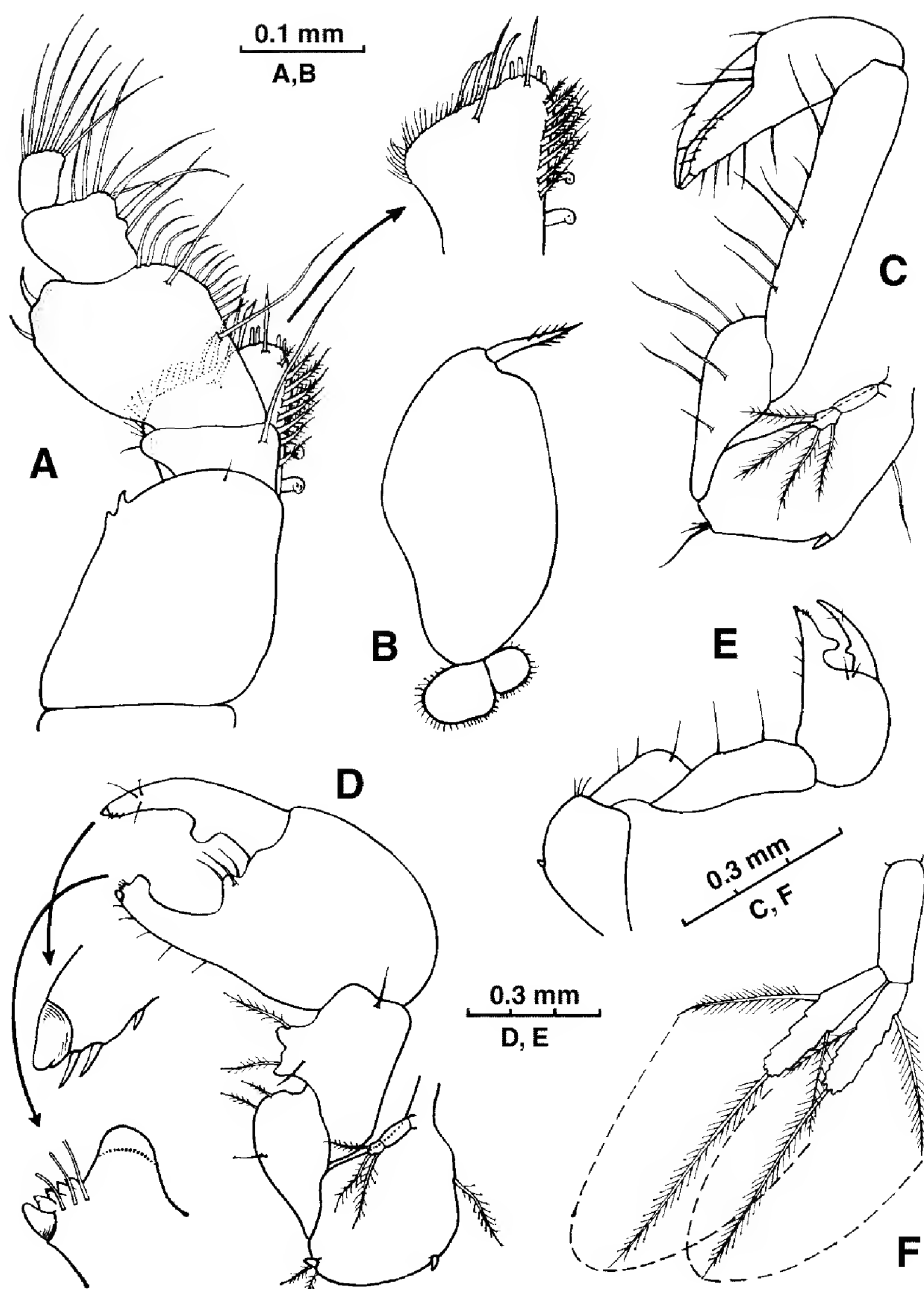
**Figure 3.** *Apseudes olimpiae* Guţu, 1986. **Female: A, maxilliped; B, epignath; C, cheliped. Male: D, adult cheliped; E, subadult cheliped, F, pleopod 1.**

Since the types are deposited in the collections of the Muséum d'Histoire naturelle "Grigore Antipa," Bucharest, we have deposited a series of specimens in the National Museum of Natural History (Smithsonian Institution) and in the Museum of the Gulf Coast Research Laboratory.

**Taxonomic status of other species of *"Apseudes"* reported from the Gulf.**

There are 3 previously published names or records of nominal species of *Apseudes* Leach, 1814 (*A.*

*propinquus* Richardson, 1902; *A. spinosus* Sars,1858, and *Apseudes alicii* King, 1966 *nomem nudum*) from waters of the Gulf (Ogle et al. 1982). There are also unpublished records in the Gulf for a small species of *Apseudes* in the *"intermedius-bermudeus* complex."

*Apseudes propinquus* has been previously reported from the Gulf and Bermudan waters (Richardson 1902, 1905, Guţu 1984, and Guţu and Iliffe 1985). Despite the presence of an anteriorly directed coxal spine on the first free pereonite, an important character for the genus *Apseudes*, Guţu and Iliffe (1985) considered this species
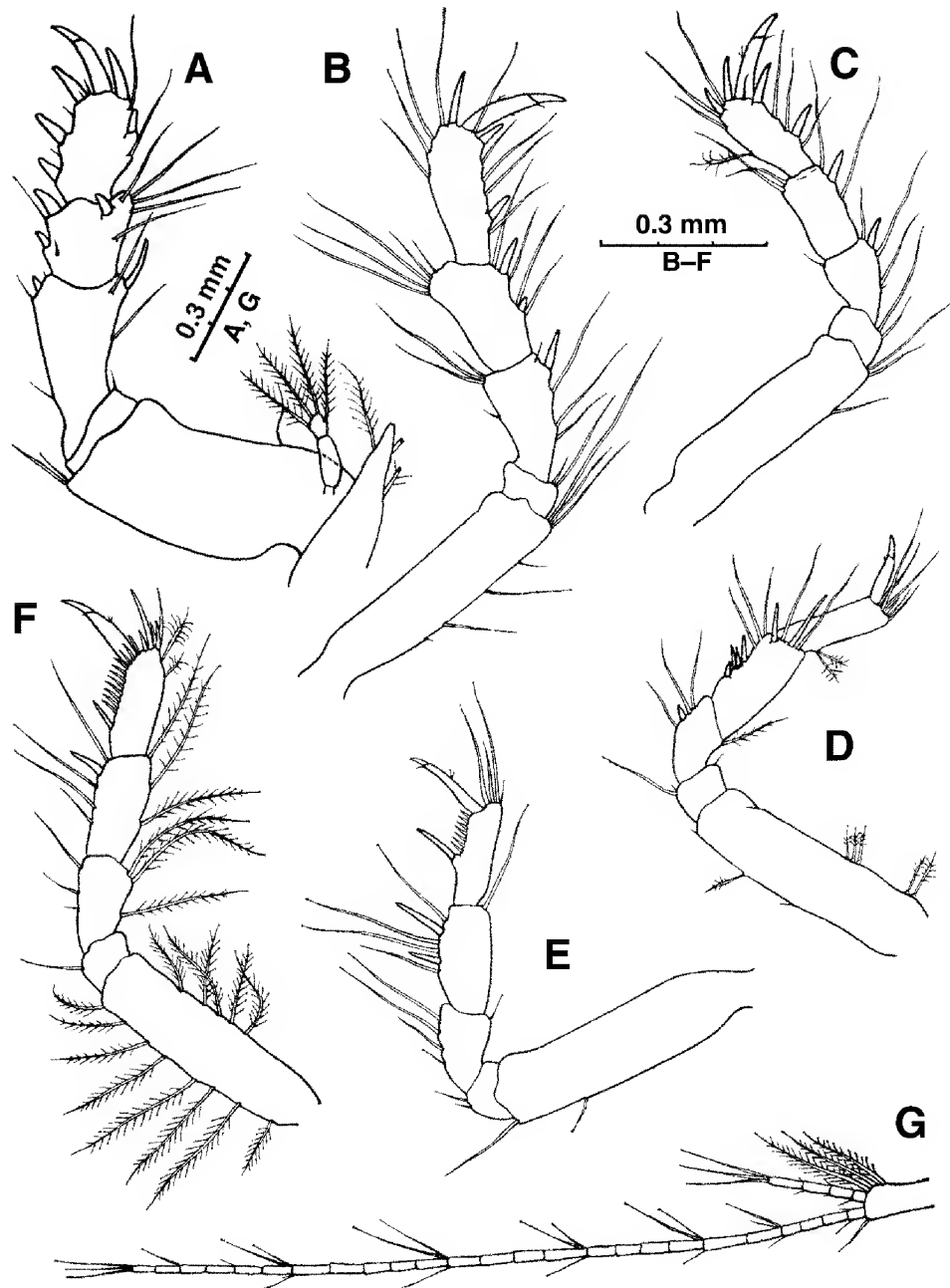
**Figure 4.** *Apseudes olimpiae* Guţu, 1986. Female: A–F, pereopods 2–7; G, uropod.

as having closer affinities to the metapseudid genus *Calozodion* Gardiner, 1983 than to *Apseudes sensu stricto*. We follow Guţu and Iliffe in considering this enigmatic species a member of the family Metapseudidae and tentatively assign it to the genus *Calozodion* sensu lato.

We have examined the material reported by Dawson (1966) as *Apseudes spinosus* from shelf waters off Louisiana. This species was originally described from waters off Norway (Sars 1899) and reliable records for this species are from the Northeast Atlantic (Sieg 1983). Dawson's material, which was deposited in the Museum

of the Gulf Coast Research Laboratory (GCRL 2813), is represented by a single adult female. Upon examination, we found the specimen to represent an undescribed species of *Apseudes sensu lato*.

The *nomem nudum* "*Apseudes alicii* King, 1966" was introduced into the published literature by Subrahmanyam et al. (1976) via an unpublished checklist to the fauna of the Appalachee Bay (Menzel 1971). Subrahmanyam et al. (1976) reported "*Apseudes* sp." from tidal marshes near St. Marks, Florida and then suggested in a note added to the proof that this species

was "probably *Apseudes allicii* King." Ogle (1977) referred to this species as "*Apseudes* n. sp. being described from Florida"; however, Sieg et al. (1982) reviewed the status of the species in question and determined that it represented a northern Gulf population of *Halmyrapsuedes bahamensis* Băcescu and Guţu, 1974. Ogle (1977) examined "type" material of "*Apseudes alicii*" deposited by King in the National Museum of Natural History and discovered that it was not an apseudid, but an undescribed species of *Kalliapseudes* Stebbing, 1910. Ogle further noted that since "*A. alicii*" had no published description, this species name should be considered a *nomum nudum* (see Sieg 1983:117).

*Apseudes intermedius sensu* Hansen, 1895, which was originally described from St. Vincent Island in the Lesser Antilles (Hansen 1895) has been collected from several locations in the Gulf, Florida Keys, and on the Bahama Banks (R. Heard and T. Hansknecht, personal observations). Băcescu (1980) designated 2 new subspecies, *A. intermedius mediterraneus* from the Mediterranean and *A. i. brasiliensis* from Brazil, and in the same publication described a very similar species, *Apseudes bermudeus* Băcescu, 1980, from a marine cave on the Bermuda Islands. *Apseudes bermudeus* and *A. intermedius* differ only slightly, and there remains the possibility, especially with availability of material from the Bahama Banks and Florida Keys for study, that they may be found to represent clinal variants of the same species. This possibility will be the subject of a future study utilizing molecular as well as classical taxonomic techniques.

The generic and specific status of "*Apseudes* sp. A." reported from shelf waters of the northwestern Gulf by Flint and Holland (1980) remain unresolved.

In conclusion, *A. olimpiae* appears to be endemic to the shelf waters of the northeastern Gulf. At present, it is the only described species of the genus *Apseudes sensu stricto* that is known with certainty from the Gulf region.

The tanaidacean fauna of the Gulf and Caribbean still remains poorly known and understood. Within the shelf waters of the Gulf there still remain many undescribed taxa, including species within the apseudomorph families Apseudidae, Parapseudidae Guţu, 1981; Kalliapseudidae Lang, 1956; Metapseudidae Lang, 1970; and Sphyrapidae Guţu, 1980 (R. Heard, T. Hansknecht, M. Guţu, personal observations). The Gulf deep water apseudomorph tanaidaceans, remain largely unknown (Pequegnat et al. 1990) with only 2 species, *Atlantapseudes lindae* Meyer and Heard, 1989 and *Pseudosphyrapus siegi* Viskcup and Heard, 1989, currently described from the region.

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## ADDENDUM

Since this paper was accepted for publication, additional records of *A. olimpiae* in North Atlantic waters have become available. A total of 17 specimens were collected as part of a NOAA /BVA project on Grays Reef (GR) off the coast of Georgia.

**Material.**—2 spec., Station GR-2, 31°24.762'N, 80°53.256'W, 03 April 2000, 19.3 m.—2 spec., Station GR-3, 31°25.15' N, 80°52.018'W, 03 April 00, 19.4 m.— 6 spec., Station GR-4, 31°24.644'N, 80°51.518'W, 03 April 00, 20.8 m.— 2 spec., Station GR-5, 31°24.923'N, 8050.288'W, 03 April 00, 21.1 m.—3 spec., Station GR-10, 31°24.348'N, 80°49.970'W, 06 April 00, 19.0 m.—2 spec., Station GR-14, 31°22.971'N, 80°51.509'W, 06 April 00, 19.3 m.

Although this additional material comes from off the US East Coast, we still believe that the type locality for *A. olimpiae* is the northeast Gulf. Based on the real and circumstantial information presented above, the presence of *A. olimpiae* on a carbonate reef off Georgia does not necessarily preclude this assumption. Because tanaidaceans lack planktonic larvae, and because there are no records of *A. olimpiae* from the South Florida Shelf in similar depths and habitat types (R. Heard and T. Hansknecht, personal observations), the presence of this species in both the Atlantic and Gulf may reflect the geological continuity of the Continental shelves during periods of high sea level in the late Oligocene. During such periods the Atlantic and Gulf populations of *A. olimpiae* may have originally evolved together in shelf waters, possibly in association with carbonate substrata, and then later became disjunct during the emergence of the Florida peninsula. Carbonate outcrops similar to Grays Reef occur in shelf waters up the East Coast to North Carolina suggesting the possibility that *A. olimpiae* might occur as far north as latitude 35°.

# Gulf and Caribbean Research

January 2001

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# GROWTH OF CAPTIVE JUVENILE TRIPLETAIL *LOBOTES SURINAMENSIS*

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*ABSTRACT* Early-juvenile tripletail *Lobotes surinamensis* (n = 27; range 45–115 mm TL, 0 = 73.0 mm; range 3.2–34.7 g TW, 0 = 12.9 g) captured in pelagic *Sargassum* algae off coastal Mississippi in mid-July 1999 were reared in a recirculating seawater system for 210 days. Fish were maintained on a natural light-dark cycle and fed to satiation 3 times per day. Water temperature ranged from 25.2° to 29.0° C and salinity was 28.0‰. All fish were measured for length and weight on days 1, 60, 135 and 210 of the study. Between these dates, mean daily TL growth rates were 2.2 mm/day, 1.2 mm/day, and 1.0 mm/day, respectively, where as 0 daily TW growth rates were 2.9 g/day, 4.3 g/day, and 7.1 g/day. Over the entire study, 0 TL and TW growth rates were 1.4 mm/day and 4.9 g/day, respectively. There was a significant correlation between length and weight vs. date of measurement. At the end of the study, specimens ranged from 272–431 mm TL (0 = 359 mm) and from 443.9–2,380.0 g TW (0 = 1,012.5 g).

## INTRODUCTION

The tripletail, *Lobotes surinamensis,* is a migratory, pelagic fish that occurs throughout the tropical and subtropical seas of the world (Fischer 1978). In the western Atlantic Ocean, tripletail is distributed from Massachusetts and Bermuda to Argentina, including the Gulf of Mexico (Gulf) and the Caribbean Sea (Robins and Ray 1986). Tripletail occur seasonally from April through October in offshore waters, sounds, bays, and estuaries along the northern Gulf coast (Benson 1982) and appear in greatest concentrations along the Mississippi coast during summer (Baughman 1941).

The life history and ecology of tripletail in the Gulf are not well known. Franks et al. (1999) reported on age and growth of tripletail from northern Gulf waters. Ditty and Shaw (1994) described larval development and distribution of tripletail in the Gulf and reported that it spawns from May through September, probably in offshore waters. Brown-Peterson and Franks (In press) reported that tripletail collected from waters offshore Mississippi were batch spawners throughout the summer. Modde and Ross (1981) collected 242 specimens (size range not given) in the surf zone of Horn Island, Mississippi during 1975–1977. Breder (1949) reported that young tripletail may frequent estuaries as nurseries, although the degree to which juvenile tripletail utilize Gulf estuaries is unknown (Ditty and Shaw 1994).

Little is known about the biology of juvenile tripletail, and there are no published data on rearing captive juvenile tripletail. Studies of juvenile fish growth are essential in order to better understand life history and

biological aspects of young fish, particularly since variability in growth rates can affect early life stage duration, potentially influencing survival and subsequent recruitment (Houde 1987). The purpose of this note is to report rearing procedures and growth rates for captive juvenile tripletail.

## MATERIALS AND METHODS

In mid-July 1999, early-juvenile tripletail (Figure 1) were captured by dip net (8.0 mm mesh) from pelagic *Sargassum fluitans* found in northern Gulf waters off the coast of Mississippi. The capture site (lat. 30°08', long. 89°01') was located about 4 km south of West Ship Island.Surface temperature and salinity at the capture site were 31.0° C and 27.0‰, respectively. Fish were immediately placed in a 45 L ice chest containing aerated seawater for transfer to The University of Southern Mississippi, Institute of Marine Sciences Aquaculture Facility. Handling of the fish was kept to a minimum to reduce stress, and time from capture to arrival at the facility was about 6h.

Juveniles selected for the growth study (n = 27) were measured for total length (TL, mm) and total weight (TW, wet weight to nearest 0.1 g) on day-1 of the study (31 July 1999). Specimens were placed in a 1.9 m³ circular tank which was part of a 1,890 L indoor, closed, recirculating system. The entire water volume was filtered about 3.5 times per h through a biological and sand filter, plus a protein skimmer. Specimens were maintained on a natural light-dark cycle and fed commercially available feed until satiated 3 times per day. During the study, water temperature ranged between

Figure 1. Photograph of a small (82 mm TL) juvenile tripletail *Lobotes surinamensis* used in the growth study.

25.2° to 29.0° C and salinity was maintained at 28.0‰. Juveniles were reared for 210 days and all specimens survived until the end of the experiment.

Since all fish were reared in the same tank, individual fish were not identifiable throughout the study; thus, growth data presented correspond to pooled specimens periodically measured during the study. Fish were weighed and measured on days 1, 60, 135, and 210, and the mean TL and TW were determined for each date. The mean daily growth rate (TL, TW) of fish for each time interval ($n = 3$) was determined as the difference between mean sizes for 2 consecutive dates divided by the number of intervening days. Correlations between mean size (TL and TW separately) vs. date of measurement were determined with the Pearson correlation coefficient (Statgraphics Plus 1998). Daily growth rate over the duration of the study was expressed as an increase in $\bar{x}$ TL and TW divided by the 210 days of the experiment. A length-weight regression ($\log_{10}$) was calculated for specimens at the end of the study.

## RESULTS

Summary TL and TW metrics for all 4 examination dates are shown in Table 1. Mean ($\pm 2SE$) TL and TW for the 27 fish on each of the 4 dates are shown in Figure 2. There was a significant correlation between $\bar{x}$ TL ($r = 0.99, P = 0.0248, n = 4$), $\bar{x}$ TW($r = 0.99, P = 0.0121$, $n = 4$), and date of measurement.

Mean daily TL and TW growth rates were calculated for specimens during the 3 time intervals (Table 1). The overall $\bar{x}$ growth rate in TL and TW for specimens during the study was 1.4 mm/day and 4.9 g/day, respectively. The highest $\bar{x}$ TW growth rate was attained during the last 75 days in captivity (Table 1). The length-weight relationship for specimens at the end of the study is: $\log_{10}TW = -12.7717 + 3.3432 \log_{10}TL$ ($r^2 = 0.836, n = 27$).
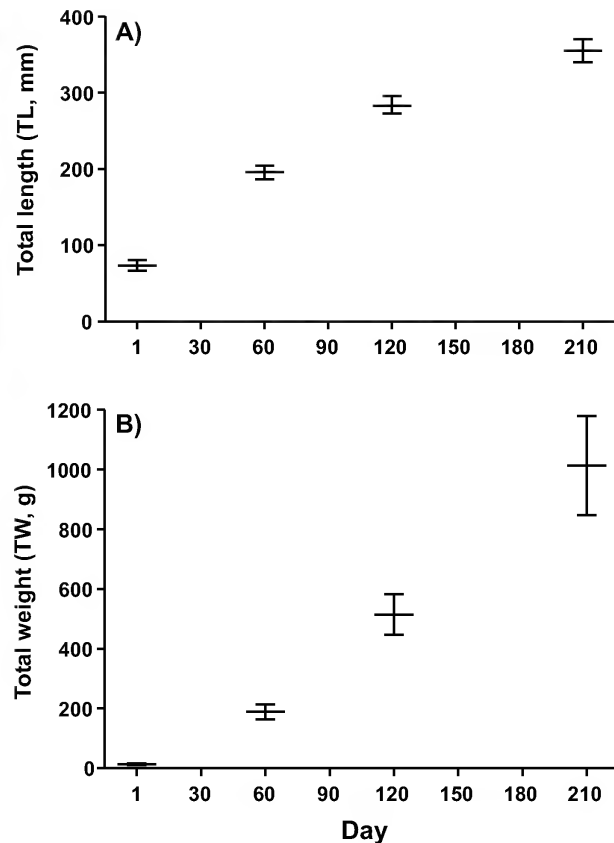


Figure 2. Plots of $\bar{x} \pm 2SE$ for total length (A) and total weight (B) for 27 juvenile tripletail *Lobotes surinamensis* 0n 4 different days during captivity.

## DISCUSSION

Based on size-at-age estimates reported for tripletail by Merriner and Foster (1974), as well as preliminary findings of age studies of tripletail from northern Gulf waters by Franks et al. (1999), all specimens used in the current study were less than one year old. Brown-Peterson and Franks (In press) reported tripletail from the northern Gulf were summer spawners (May through August), and juveniles used in our study most likely were spawned during the early part of the reproductive season.

To our knowledge, this study represents the only study in which early-juvenile tripletail were collected in the wild and reared in captivity for growth studies. An undesirable aspect of our study was the necessity of rearing all juveniles in one tank, thereby making it impossible to determine specific growth rates for individual specimens. However, the periodic and overall TL and TW growth rates calculated for the sample represent important information on growth of young tripletail.

Tripletail grow rapidly during the first year of life. Mean TL and TW of juveniles at the end of the study were 359 mm and 1,012.5 g, respectively. The largest

68

## TABLE 1

**Summary of body size metrics and mean growth rates for juvenile tripletail (*n* = 27) captured off coastal Mississippi and used in the growth study. Growth rates shown are the mean daily growth between 2 consecutive dates.**

| Date | Total length (mm) | | | Growth mm/day | Total weight (g) | | | | Growth g/day |
|------|-------|------|------|------|-------|------|------|------|------|
| | Range | Mean | SE | | Range | | Mean | SE | |
| 07-30-99 | 45.0–115.0 | 73.6 | 3.56 | | 3.2– 34.7 | 12.7 | 1.54 | | |
| | | | | 2.2 | | | | | 2.9 |
| 09-28-99 | 160.0–235.0 | 195.5 | 4.56 | | 100.0–319.6 | | 188.7 | 12.66 | |
| | | | | 1.2 | | | | | 4.3 |
| 12-15-99 | 210.0–350.0 | 282.9 | 6.53 | | 274.1–795.0 | | 514.1 | 33.99 | |
| | | | | 1.0 | | | | | 7.1 |
| 02-09-00 | 272.0–431.0 | 355.0 | 7.59 | | 443.9–2,380.0 | | 1,012.5 | 83.02 | |

fish attained a size of 431 mm TL and 2,380.0 g TW. On the final day of the study, 14 fish (52%) exceeded 350 mm in TL and 11 fish (41%) exceeded 1,000 g in TW. Juveniles demonstrated a progressively slower $\bar{x}$ growth rate in TL, whereas there was a conspicuous increase in $\bar{x}$ TW.

Although the study was conducted in an indoor facility, the south wall of the room which housed the rearing system contained large windows designed to allow natural light to enter throughout the day. Even though the room was heated during winter, water temperature varied seasonally. Water temperature at the beginning of the study (July 1999) was 29° C, averaged 28.1° C for the following 2 warm-weather months, then gradually decreased over the next 5 months ($\bar{x}$ = 26° C) until termination of the study in February 2000 (25.2° C). The fish increased substantially in $\bar{x}$ TW over the entire range of water temperature, with the largest $\bar{x}$ growth in TW occurring during the latter part of the study when water temperatures were lowest.

Juveniles were fed to satiation throughout the study, which necessarily required an increase in the amount of food with increased time. The quantities of food provided the fish were not well documented, and we did not examine food/fish growth relationships or feed conversion ratios. Future experimental rearing of juvenile tripletail should include constant documentation of rations and investigation of the synergistic effects of different feeds and water temperatures on the growth of young tripletail. The growth rates reported here might represent near-upper limits for captive juvenile tripletail which are fed manufactured food. No published information exists on growth of juveniles in rearing systems or in the natural environment for purposes of comparison with our findings.

Since the early life stages of tripletail are spent in the epipelagic zone (Ditty and Shaw 1994) where predation risk for small fishes is considerable, the rapid growth observed for juveniles in captivity may be characteristic of young tripletail in the wild. Our specimens were collected from floating *Sargassum* which provides some measure of protection for young fishes as they drift with the algae (Dooley 1972). Baughman (1943) reported that juvenile tripletail often associate with pelagic *Sargassum*. However, the size at which young tripletail become associated with *Sargassum* habitat is unknown (Ditty and Shaw 1994).

Additional research on growth of young tripletail under controlled laboratory conditions, and in nature, is needed to better understand how physical and biotic variability in the marine environment affects growth rates, recruitment and life stage duration.

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# Morphology of the First Zoeal Stage of *Platypodiella spectabilis* (Herbst, 1794) (Decapoda, Brachyura, Xanthidae) Obtained in the Laboratory

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# MORPHOLOGY OF THE FIRST ZOEAL STAGE OF *PLATYPODIELLA SPECTABILIS* (HERBST, 1794) (DECAPODA, BRACHYURA, XANTHIDAE) OBTAINED IN THE LABORATORY

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*Abstract* Ovigerous females of the xanthid crab *Platypodiella spectabilis* (Herbst, 1794) were obtained from 2 widely separated localities: the Ubatuba coast (Félix Beach, São Paulo) of Brazil and Guana Island in the British Virgin Islands (BVI). First stage zoea larvae were obtained from females at both locations. Those from Brazil are described and illustrated. The first zoea bears dorsal, rostral, and lateral carapace spines, plus a well-developed and spinose antennal protopod that bears a greatly reduced exopod with 2 minute setae. This antennal morphology, along with other characters, places the species among the "Group I" xanthid zoeas of Rice (1980) and Martin (1984, 1988). Differences between larvae from Brazil and those from the BVI are minor and are attributed to within-species variation. Characters that serve to separate these larvae from those of co-occuring xanthids are presented. Comments on the distribution and size of *Platypodiella spectabilis* are included.

## INTRODUCTION

The xanthid crab genus *Platypodiella* was erected in 1967 (Guinot 1967:562) to accommodate 4 species formerly treated as *Platypodia* Bell, 1835. Two of the species, *P. gemmata* (Rathbun, 1902) and *P. rotundata* (Stimpson, 1860), are known from the eastern Pacific. Garth (1991:131), in discussing the Galapagos crab fauna, pointed out that the 2 Pacific species are possibly the adult (described as *P. rotundata*) and young (*P. gemmata*) of the same species, with the name *P. rotundata* having precedence. Other workers feel that the 2 Pacific species are distinct (T. Zimmerman, personal communication, Natural History Museum of Los Angeles County, Los Angeles, CA, USA). The other 2 species are Atlantic, with *P. picta* (A. Milne Edwards, 1869) restricted to the eastern Atlantic and *P. spectabilis* (Herbst, 1794) known from the western Atlantic.

*Platypodiella spectabilis* is a relatively small xanthid found in or near coral reefs and rocky shorelines throughout most of the western Atlantic. The species has been reported as far north as Bermuda (Chace et al. 1986:346, plates 115 and 11:11, in Sterrer 1986, as *Platypodia spectabilis*) and as far south as Rio de Janeiro, Brazil, including the Fernando de Noronha Archipelago and Trindade Island (Melo 1998:490). The current report extends the southern range to the São Paulo state of Brazil. Thus, the range of the species is an impressive 7,000 km from northern to southern extent. Distribu-

tional records within this range, and extending westward into the Gulf of Mexico, can be found in Rathbun (1930), Felder (1973), Powers (1977), and Abele and Kim (1986). Because of its spectacular coloration and color pattern, *P. spectabilis* is often depicted in faunal or regional guide books (Humann 1992), and the species is sometimes referred to as the calico crab (Chace et al. 1986) or gaudy clown crab (Williams et al. 1989).

The use of crab larval morphology, and in particular characters of the first zoeal stage, in elucidating phylogeny is now well established (see references in Clark et al. 1998) especially within the Xanthidae (Clark and Al-Aidaroos 1996, Clark and Galil 1998, Clark and Ng 1998). To date, nothing is known about larval development in the genus *Platypodiella*, and thus no larval evidence has been brought to bear on the question of how this genus relates to other genera within the Xanthidae *sensu stricta* or to other families within the superfamily Xanthoidea (sensu Martin and Davis, in review). In this paper we provide the first description of zoeal larvae in this genus.

## MATERIALS AND METHODS

In February 1998, four ovigerous female *P. spectabilis* were collected by scuba diving along the infralittoral region of a rocky shore (Félix Beach) in Ubatuba, São Paulo, Brazil (23°23'00"S, 44°57'06"W). The crabs were maintained separately in an aquarium

provided with seawater from the collecting site (salinity 35‰, temperature 24 ± 1°C) until hatching. The eggs of 2 of these females, carapace widths 28.1 and 29 mm, hatched. Newly hatched zoeae were fixed in 10% formalin and were then transferred to a mixture (1:1) of 70% ethyl alcohol and glycerin; 15 specimens were dissected for detailed examination and description. Additional ovigerous females were collected from the eastern Caribbean as part of an ongoing survey of the marine invertebrates of Guana Island, British Virgin Islands (BVI) (led by T.L. Zimmerman and J.W. Martin). These specimens came from North Beach, Guana Island, from interstices of dead coral (mostly clumps of dead *Porites*) in shallow water (1 m and less), on 14 July 2000 (Station 65 of the Zimmerman/Martin survey of Guana Island). A single ovigerous female (later photographed alive, photographic voucher number Vc0796), carapace width 10.5 mm, carapace length (as measured from front to back and excluding the rostrum) 7.1 mm, was kept alive in a small plastic container of fresh seawater until the eggs hatched later that evening. Examination of these larvae occurred in the laboratory of the 3rd and 4th authors in Los Angeles.

Illustrations were made from fixed material and are based on at least 15 specimens (Brazil) or 5 specimens (BVI). First stage zoeae were dissected under a stereomicroscope and mounted on semi-permanent slides. Morphological characters were examined with a Zeiss Axioskop 2 compound microscope attached to a personal computer using an Axiovision Image Analysis system (Brazil) or a Wild M5APO dissecting microscope and Nikon Labophot compound microscope with drawing tube (Los Angeles, for the BVI specimens). For the description of the larvae we followed the format suggested by Clark et al. (1998). Larvae and one parental female from Brazil have been deposited in the collection of the Departamento de Zoologia, Instituto de Biociencias, UNESP, Botucatu, SP, Brazil, NEBECC/LC 00076.1 (larvae) and NEBECC/LC 00076.0 (female). Larvae and the parental female from the BVI have been deposited in the collections of the Natural History Museum of Los Angeles County (LACM CR 20000061), as has a second large ovigerous female from Brazil (LACM CR 19981421).

## RESULTS

**Size.** Larvae from the Brazilian female were slightly longer than those from the BVI, averaging 1.43 ± 0.18 mm from tip of rostrum to tip of dorsal spine (compared to 1.20 mm for BVI larvae) and 0.53 ± 0.03 mm total

carapace length (compared to 0.42 mm in BVI larvae). However, width of the larvae from the 2 localities was the same; both Brazilian and BVI larvae averaged 0.79 ± 0.04 mm from tip to tip of the lateral carapace spines.

**Carapace (Figure 1a, 3a).** Globose, bearing dorsal, rostral, and lateral spines. Lateral spines shorter than dorsal and rostral spines. Rostral spine with 2 to 6 spinules (always 6 in Brazilian specimens) along mediodistal two thirds. Eyes sessile.

**Abdomen (Figure 1b).** With 5 abdominal somites, each bearing pair of posterodorsal setae. Somite 2 bearing lateral knobs projecting anteriorly and dorsally. Somite 3 bearing small lateral knobs projecting laterally or posterolaterally. Somites 3–5 with acute posterolateral processes. Pleopods absent.

**Telson (Figure 1b, 3b).** Bearing on each branch one large lateral spine, one small seta-like spine directly posterior to large lateral spine, and one short dorsal spine located posterior to these. Three pairs of minutely serrate spines on posterior emargination; innermost pair with 3
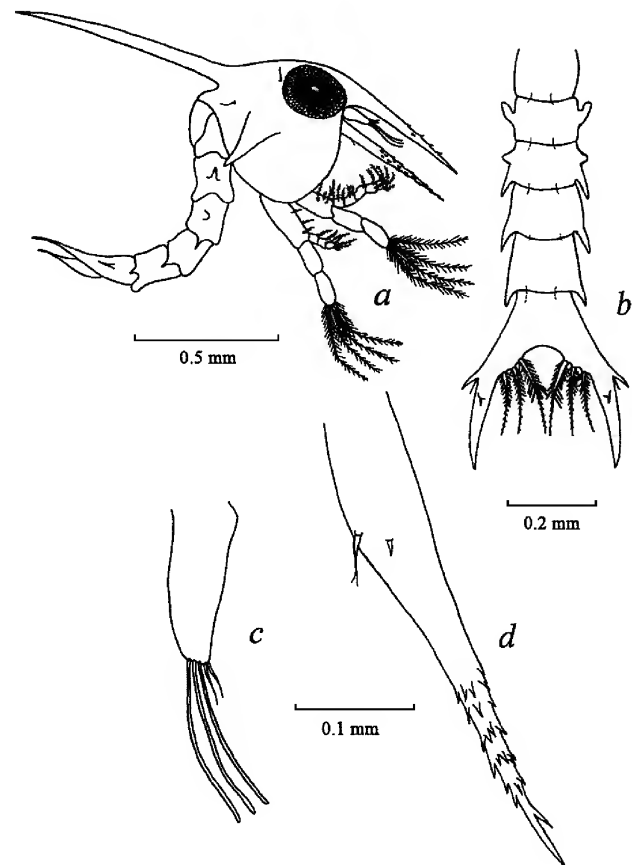


**Figure 1. Morphology of the first zoea of *Platypodiella spectabilis* (based on specimens from Brazil). a, entire zoea, lateral view. b, abdomen and telson, dorsal view. c, antennule. d, antenna.**

or 4 setules at approximate midlength in addition to serrations.

**Antennule (Figure 1c, 3c).** Uniramous. Endopod absent. Exopod unsegmented, with 3 aesthetascs (Brazil; only 2 in BVI) and 2 simple setae.

**Antenna (Figure 1d, 3c).** Protopod well developed, as long as rostral spine, and distally spinulate. Endopod reduced, represented by small spine at 1/3 length of protopod. Exopod greatly reduced, less than 1/10 length of protopod, and bearing 2 minute simple setae.

**Mandible (Figure 2a).** Incisor process stout. Molar process well developed. Endopod palp absent.

**Maxillule (Figure 2b).** Basial endite with 2 plumodenticulate to cuspidate setae, 2 plumodenticulate setae and 1 plumose setae. Coxal endite with 5 plumodenticulate setae and 1 plumose seta. Endopod 2-segmented, with 1 plumose seta on proximal article and 6 plumose setae (2 subterminal + 4 terminal) on distal article.

**Maxilla (Figure 2c).** Coxal endite bilobed with 4 + 4 plumodenticulate setae. Basial endite bilobed with 4 + 4 plumodenticulate setae. Endopod bilobed with 3 + 5 (2 subterminal + 3 terminal) plumodenticulate setae. Scaphognathite with 4 marginal setose setae and stout posterior process.

**First Maxilliped (Figure 2d).** Coxa with one plumose seta. Basial segment with 10 medial plumose setae arranged 2, 2, 3, 3. Endopod 5-segmented with 3, 2, 1, 2, and 5 plumose setae. Exopod 2-segmented with 4 terminal plumose setae.

**Second Maxilliped (Figure 2e).** Coxa without setae. Basial segment with 4 medial plumose setae arranged 1, 1, 1, 1. Endopod 3-segmented, with 1, 1, and 2 subterminal + 3 terminal plumose setae. Exopod 2-segmented, with 4 terminal plumose setae.
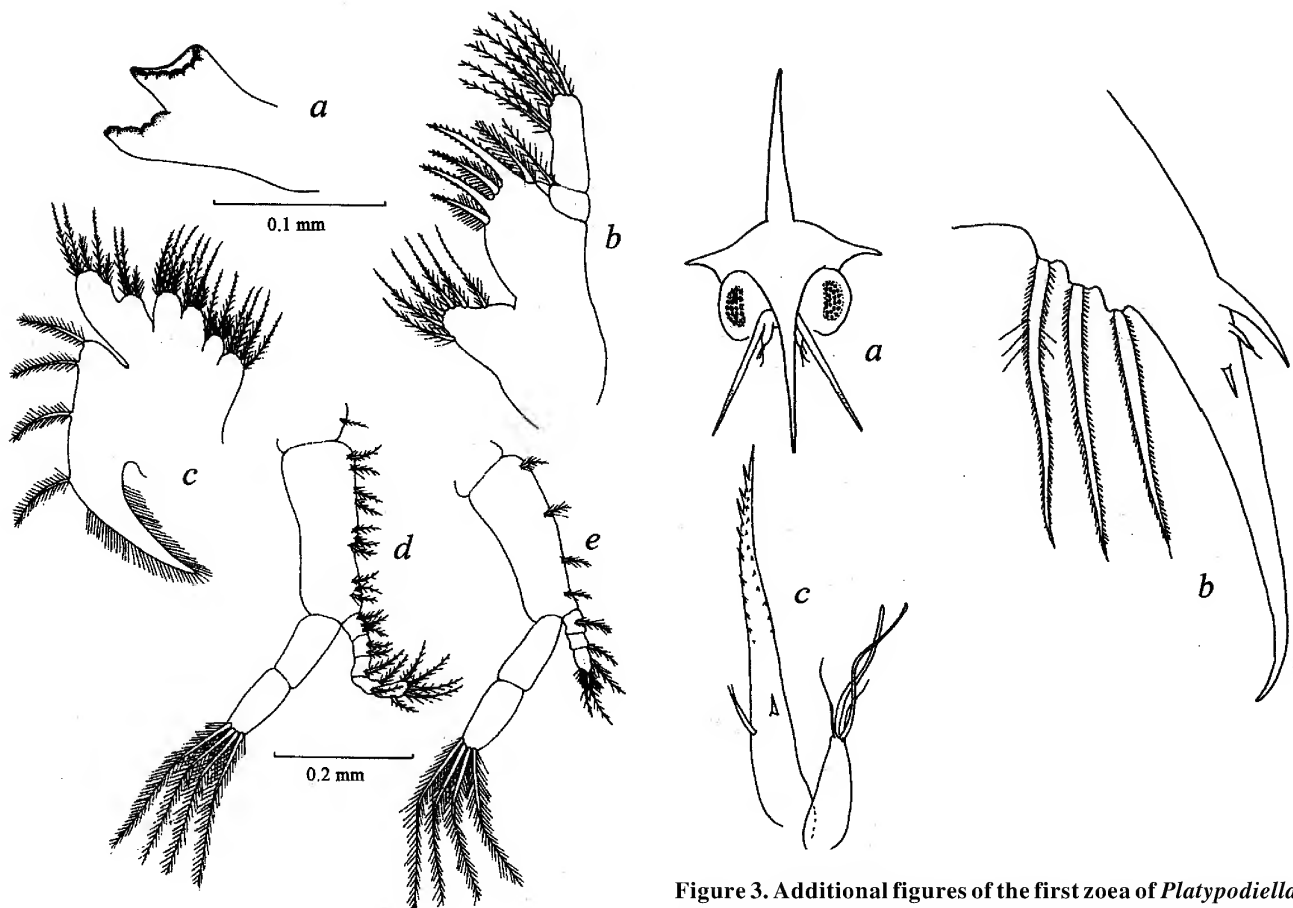


**Figure 2. Morphology of the first zoea of *Platypodiella spectabilis* (based on specimens from Brazil). a, mandible. b, maxillule. c, maxilla. d, first maxilliped. e, second maxilliped.**

**Figure 3. Additional figures of the first zoea of *Platypodiella spectabilis* from a female collected in the British Virgin Islands. a, frontal view showing relative lengths of lateral and dorsal carapace spines. b, right fork of telson and right side setae, dorsal view. c, antenna (left) and antennule (right).**

## REMARKS AND DISCUSSION

### Comparison of larvae from Brazil with those from the eastern Caribbean

Larvae from Guana Island (BVI) differ from those from Brazil only slightly. Brazilian larvae were longer, based on measurements of the rostral-to-dorsal spine lengths, but were equally wide (lateral spine tip-to-tip length). Rostral spinules were fewer in the BVI specimens, with sometimes as few as only 2 spinules, whereas Brazilian larvae always possessed 6 rostral spinules. Aesthetascs of the antennule usually numbered 2 in the BVI specimens but 3 in the Brazilian specimens. Placement of the 2nd (smaller) lateral spine on the telson appeared to be slightly more posterior in the BVI specimens (compare Figures 1b and 3b), although this may be only a matter of interpretation of the illustrator. Thus, despite the geographic distance separating the parental females, larvae from the 2 areas are quite similar.

### Observations on hatching behavior of the parental female

The parental female collected in the BVI was observed from the time of collection (late afternoon) until about 0130 the following morning. Hatching of the eggs commenced at about 1930 on July 14. As hatching began, the female began rhythmically pumping her abdomen at a rate of about 1 pump per second, with a pattern of 4 or 5 pumps followed by a short pause, followed by 4 or 5 pumps, followed by another pause. This rhythmical pumping continued for several hours, gradually slowing at 0130 the next morning (15 July), at which time the female and her remaining eggs were preserved. At the time of preservation, there were still a large number (we estimate about 1/10) of the original number of eggs remaining on the pleopods. It is not known if these eggs would have continued to hatch throughout the night. Thus, hatching in this species can take at least 5 hours based on these limited laboratory observations. The effects of captivity and confinement in a small container are unknown; these factors also could play a role in the crab's behavior.

### Systematic position of *Platypodiella* based on larval morphology

The reduced antennal expopod, well-developed lateral carapace spines, and setation of the endopods of the maxilla, maxillule, and both maxillipeds all combine to suggest that *Platypodiella* belongs among the Group I xanthid zoeas of Rice (1980) and Martin (1984). Within this group, *Platypodiella* belongs to a subgroup that bears spinules on the protopod of the antenna (see below).

Guinot (1967), when erecting the genus *Platypodiella*, remarked on the similarities between species of this genus and those of *Platyactaea* Guinot, 1967, and to a lesser extent to species of *Atergatis* De Haan, 1833 and *Atergatopsis* A. Milne Edwards, 1862, as well as to members of *Platypodia*. The latter 3 genera are usually considered members of the xanthid subfamily Zosiminae (Serène 1984, Clark and Ng 1998). Thus, one might expect to find morphological and zoeal similarities among species of these genera. To our knowledge, within these genera descriptions of the first zoea exist only for *Atergatis* (Terada 1980) and for *Platypodia* (Hashmi 1970). Larvae of another Zosiminae genus, *Lophozozymous*, were recently described by Clark and Ng (1998). Martin (1984) placed *Atergatis* (based on Terada's description of the larvae of *A. reticulatus* DeHaan, 1835) in Group I, but was indecisive about Hashmi's (1970) description of the zoea of *Platypodia cristata* (A. Milne Edwards, 1865), and left it in an "incertae" grouping of xanthid larvae having no clear affinities. Hashmi (1970) did not provide illustrations of any larval features of *P. cristata*, instead indicating the antennal and telson "types" using a schematic diagram. The antenna of *P. cristata* was categorized by Hashmi (1970) as "type b," where the antennal exopod was at least half the length of the protopod. Thus, in this feature there is a significant difference between larvae of *Platypodia* and larvae of *Platypodiella*.

Concerning relationships of *P. spectabilis* to the numerous and diverse families of "xanthoids" (treated as the superfamily Xanthoidea, containing 12 families, by Martin and Davis in review): the rostral and antennal morphologies of the zoea of *P. spectabilis* may indicate an affinity with the subfamily Panopeinae (the Panopeidae of Guinot 1978, and Martin and Davis in review). The zoea of *P. spectabilis* is also similar to those of the Indo-Pacific *A. reticulatus* (as described by Terada 1980), sometimes considered a member of the xanthoid subfamily Zosiminae (Serène 1984). Clark and Ng (1998) correctly note that antennal morphology alone is insufficient for determining subfamiliar affinities within the xanthoids.

### Comparison of the larvae of *P. spectabilis* with those of other western Atlantic xanthoids

Martin (1984), in his review of the larvae of xanthid crabs, listed some 25 species of xanthids (sensu largo) from the western Atlantic and Gulf of Mexico for which at least the first zoeal stage was described. Most of these

74

(15) belonged to the Group I larvae as described above. Since that time several other descriptions of western Atlantic xanthid larvae have appeared (seeMartin et al. 1985 for *Panopeus bermudensis* Benedict and Rathbun, 1891; Iorio and Boschi 1986 for *Platyxanthus patagonicus* A. Milne Edwards, 1879; Negreiros-Fransozo 1986a, b for *Panopeus americanus* De Saussure, 1857 and *Eurypanopeus abbreviatus* Stimpson, 1860, respectively; Fransozo 1987 for *Eriphia gonagra* (Fabricius, 1781; Ingle 1985 for *Panopeus occidentalis* De Saussure, 1857; Ingle 1987 for *Cataleptodius floridanus* (Gibbes, 1850); Montú et al. 1988 for *Panopeus austrobesus* Williams, 1983; Martin 1988 for a review of xanthid larvae and information on phyletic utility of the megalopa stage; Bakker et al. 1989 for *Hexapanopeus schmitti* Rathbun, 1930; Fransozo et al. 1990 for *Hexapanopeus paulensis* Rathbun, 1930; Messerknecht et al. 1991 for *Eurytium limosum* [previously described by Kurata et al. 1981]; and Vieira 1999 for *Hexapanopeus caribbaeus* (Stimpson, 1871).

The first zoeal stage of *P. spectabilis* is very similar to the first zoea of a large number of western Atlantic xanthids. However, it can be readily distinguished from larvae of any of the previously described western Atlantic species by 2 characters. First, the antennal exopod is greatly reduced (true of all "Group I" xanthid zoeas), while the antennal protopod bears rows of spines on the distal 1/4 to 1/2 of its length. In this character, the first zoea of *P. spectabilis* is similar to existing descriptions of the first zoeal stage of *P. occidentalis*, *P. herbstii*, *P. americanus*, *P. austrobesus*, *E. limosum*, *Eurypanopeus abbreviatus*, *E. depressus*, *C. floridanus*, and *H. paulensis*. Second, the spinules on the rostral spine are known only for this species and for the first zoeas of *Garthiope barbadensis* (Rathbun, 1921), formerly *Micropanope* Stimpson, 1871 (Gore et al. 1981) and *C. floridanus* (Ingle 1987). The rostral spine of *P. spectabilis* can bear up to 6 sharp spinules, whereas first zoeal larvae of *G. barbadensis* and *C. floridanus* were each described as having only 2 such spinules.

**Geographical Distribution**

The distribution of *P. spectablis* as presently understood (i.e., assuming that there is a single species in the western Atlantic rather than a species complex) is in excess of 7,000 km. When we add to this the fact that *P. spectabilis* is found in the far western Gulf of Mexico (Felder 1973) and far eastern Caribbean (e.g., British Virgin Islands, this report), it becomes clear that the range of the species is extraordinarily large. However, such a range is not unique; there are other species of

xanthoid crabs (e.g., *Eriphia gonagra* and *Carpilius corallinus* (Herbst, 1783) that have similar ranges (T. Zimmerman, personal communication, Natural History Museum of Los Angeles County, Los Angeles, CA, USA). It is possible that the spectacular color pattern, from which the species derives its name, has caused workers to quickly and easily "identify" all of the various color forms (see description of color variation in Chace et al. 1986) as *P. spectabilis*. Because cryptic species are being discovered frequently on the basis of subtle color differences (see Zimmerman and Felder 1991 for species of *Sesarma* Say, 1817; Williams and Felder 1989 for species of *Menippe* De Haan, 1833), it is certainly possible that the wide range of colors and color patterns in *P. spectabilis* is hinting at a species complex rather than one wide-ranging species. If such is the case, it is also possible that we have misinterpreted the differences in larvae from the eastern Caribbean and Brazil (where the adult females are nearly 3 times the size of those in the BVI) as being caused by intraspecific, rather than interspecific, variation. On the other hand, this species can exhibit a wide range of colors and patterns within a very small geographic region (T.L. Zimmerman and J.W. Martin, unpublished data). Clearly more work on morphological and color variation in this species across its entire range is needed.

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# Gulf and Caribbean Research

Volume 13 | Issue 1

January 2001

# The Stomatopod *Alachosquilla floridensis* (Manning, 1962) (Crustacea, Stomatopoda, Nannosquillidae) Reported from Guana Island, British Virgin Islands, with Observations on Color

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# THE STOMATOPOD *ALACHOSQUILLA FLORIDENSIS* (MANNING, 1962) (CRUSTACEA, STOMATOPODA, NANNOSQUILLIDAE) REPORTED FROM GUANA ISLAND, BRITISH VIRGIN ISLANDS, WITH OBSERVATIONS ON COLOR

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## INTRODUCTION

Although color pattern can vary among and within species of the Crustacea, it can also be a conservative feature that can be very helpful in field identifications. This is often the case in the Crustacea Decapoda, where sibling species can be detected by subtle differences in color (e.g., Williams and Felder 1989, Zimmerman and Felder 1991, Knowlton and Mills 1992). Stomatopods are among the most colorful crustaceans when living. Many species show a great deal of variability (Manning 1969, Camp 1973), and knowledge of this coloration is often key to their identification in the field and in the lab (Schotte and Manning 1993).

As part of an ongoing survey of the marine invertebrate fauna of Guana Island, British Virgin Islands, we collected 2 large (45 mm and 48 mm TL) females, and one male specimen (30 mm TL) of the rarely reported stomatopod species *Alachosquilla floridensis* (Manning 1962). To our knowledge, the species has been reported previously in the literature only 4 times (see Schotte and Manning 1993). These reports are based on a total of 8 specimens. Previous distribution records for the species include Lake Worth Inlet, Florida; Virgin Gorda, US Virgin Islands; Isla Marguerita, Venezuela; Bahia, Brazil; and Saint Giles Island and London Bridge Rock, Tobago, West Indies (Manning 1969, Schotte and Manning 1993).

*Alachosquilla floridensis* was first described as *Lysiosquilla floridensis* by Manning (1962). The species was transferred to the genus *Acanthosquilla* by Manning (1963), along with *L. digueti* (Coutière 1905) from the eastern Pacific. Later, Manning (1974) synonymized *A. floridensis* with *A. digueti*. Subsequently Schotte and Manning (1993) recognized the differences between the 2 species, and also placed the 2 into a newly created genus, *Alachosquilla*.

## MATERIALS AND METHODS

Two female and one male specimens of the stomatopod *Alachosquilla floridensis* (LACM CR1999020.1,

48 mm TL female; LACM CR1999020.2, 45 mm TL female, and 30 mm TL male), cataloged in the Crustacea collections of the Natural History Museum of Los Angeles County, were collected from shallow subtidal waters (1–1.5 m) along White Beach, a protected calcareous sand beach on Guana Island, British Virgin Islands, on 6 August 1999. They were collected using a stainless steel "yabby pump" suction device (see Manning 1975) while collecting callianassid shrimp (*Neocalichirus* spp.). It is not known if the stomatopods were sharing the callianassid burrows or had formed their own. Although 3 species of *Neocalichirus* were collected at this time, no specimens were brought up with the stomatopods, and no balanoglossids were seen.

Specimens were taken directly to the lab and chilled on ice until dead, at which time the larger female (LACM CR1999020.2) was photographed. Digital images were cleaned (backgrounds were replaced with solid black, and the images were adjusted for brightness and filtered using "unsharp mask") using Adobe Photoshop 5.5 software.

## RESULTS

The dorsal and lateral integument is bright white. More-or-less transparent regions across the middle of each abdominal somite and between somites allow the orange-tan colored ovary to show through (Figure 1a, b) in the females. In our preserved specimens, dark chromatophores are present, forming very thin lines along the posterior margin of each abdominal somite. Two widely spaced spots of chromatophores occur at the posterior margin of the 5th abdominal somite. On the dorsal surface of the telson, a short longitudinal band of chromatophores lies on either side of the median dorsal tooth (Figure 1a, 2a). Manning (1969, Figure 16b) showed these bands as surrounding the bases of the 2 flanking teeth, and Schotte and Manning (1993, Figure 3b) omitted them from their figure altogether, but mentioned them in the text. This is the pigmentation pattern used to separate *A. floridensis* from its only eastern Pacific congener, *A. digueti*, which has but one central coalesced
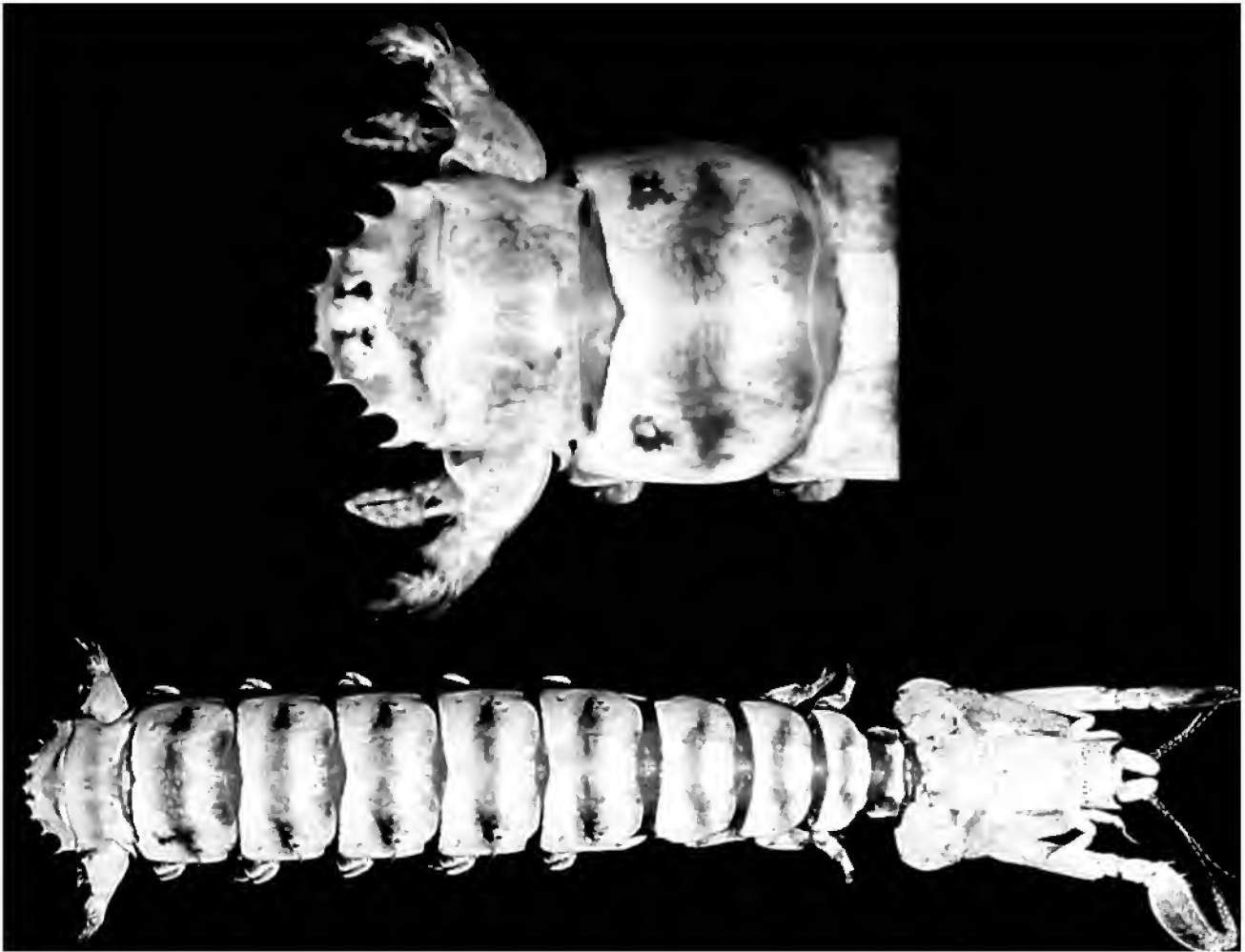
**Figure 1. Color pattern of a fresh specimen of** *Alachosquilla floridensis* **(Manning, 1962) LACM CR1999020.2; a = close up of telson and posterior somites in dorsal view; b = whole animal in dorsal view.**

spot. On the ventral surface of the telson, a small field of chromatophores can be seen posterior to the anus on one specimen. A dark crescent of chromatophores occurs at each posterolateral corner of the carapace. Scattered chromatophores also occur on the carapace, rostral plate, and eyestalks.

In all of our specimens (one preserved using only 75% EtOH = LACM CR1999020.1, and 2 fixed first in 10% formalin =LACM CR1999020.2) the teeth of the rostral plate extend only to the bases of the ocular peduncle, and the bases of the eyestalks are plainly visible. The expanded, fused ocular scales are clearly visible, protruding laterally from under the proximal half of the median rostral spine (Figure 2b).

## DISCUSSION

Description of the animal's habitat is scattered. The type specimen came from "Shoreline" along Cape Florida, Key Biscayne, Florida (Manning 1962). Brazilian specimens (from Praia do Araçá) came from a very sheltered beach between normal low and extremely low tide level (Rodrigues 1971) with sediments consisting of layers of fine sand (predominantly 0.1–0.07 mm) overlying strata of gravel (Burdon-Jones 1969, p. 256, Appendix 1). Habitat notes for Tobago specimens include: "Sublittoral, in 6–11 and 13–28 m; from rock, rubble, with live and dead coral, 6–11 m; and vertical rock wall to ledge, 13–28 m. This species, which burrows in level bottom substrates, certainly was taken from sand on the ledge rather than on the wall itself" (Schotte and Manning 1993: 573). Rodrigues (1971) mentioned taking *A. floridensis* with balanoglossids in Brazil in his original account of *Callianassa* (=*Sergio) gaussitinga.*
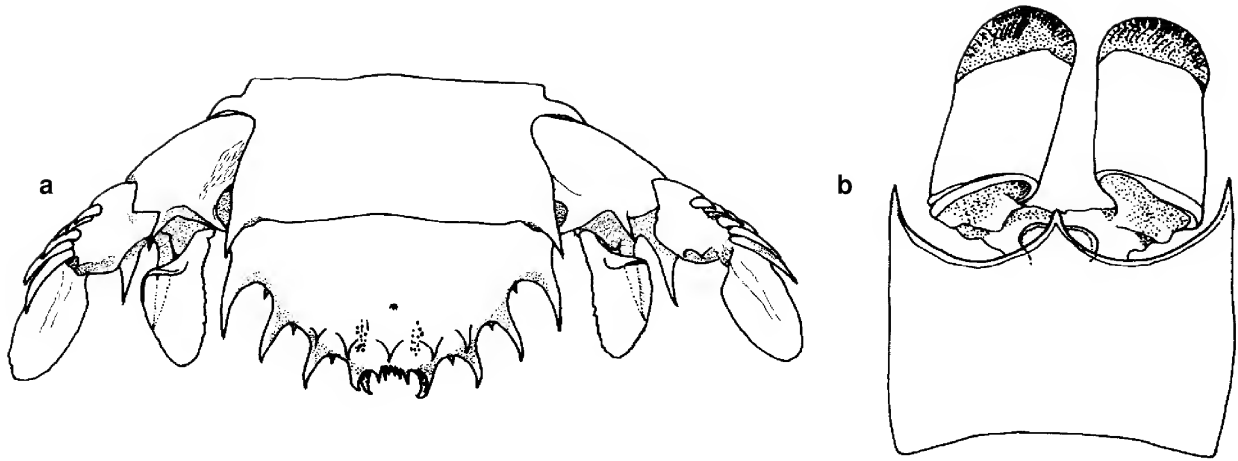
80

**Figure 2. Diagnostic characters of** *Alachosquilla floridensis* **(Manning, 1962) from LACM CR1999020.1; a = telson and 6th abdominal somite, dorsal view (setae omitted); b = head in dorsal view.**

Morphologically, and especially in regard to the very distinctive rostrum, our specimens agree with the figures and descriptions provided by Manning (1962, 1969) and Schotte and Manning (1993). One subtle difference is in the amount of head covered by the rostral plate, but this may be due to the relaxed death of the animals (D. Camp, personal communication, P.O. Box 4430, Seminole, FL 33775-4430).

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# Gulf and Caribbean Research

Volume 13 | Issue 1

January 2001

Gulf Estuarine Research Society Fall 2000 Meeting Abstracts

# GULF ESTUARINE RESEARCH SOCIETY

## FALL 2000 MEETING

The Fall 2000 meeting of the Gulf Estuarine Research Society (GERS) was held at the Holiday Inn in Hammond, Louisiana on Monday and Tuesday, November 13 and 14, 2000. Local arrangements were organized by Denise J. Reed (University of New Orleans) and Robert W. Hastings (Southeastern Louisiana University) with significant support from Carolyn Woosley and Dr. Gary P. Shaffer. The Scientific Program was organized by Mark S. Peterson (The University of Southern Mississippi).

| | | |
|---|---|---|
| Monday, November 13 | 5:00-6:00 pm | GERS Registration Table |
| | 5:00 pm | Posters set up in Veranda Room |
| | 7:00 pm -until | GERS Reception at the Shaffer Home |
| | | |
| Tuesday, November 14 | 7:30 am-12:00 pm | GERS Registration Table |
| | 8:00 am | Coffee in Veranda Room |
| | 8:30-10:00 | Sessions |
| | 10:00-10:30 | Break and Poster Session |
| | 10:30-11:30 | Sessions |
| | 11:30-1:00 | Lunch |
| | 1:00-4:30 | Sessions |
| | 2:30-3:00 | Break and Poster Session |
| | 3:00-4:00 | Sessions |
| | 4:30-5:30 | Student Awards and Business Meeting |

Underlined name indicates the presenter and an asterick [*] indicates a student presentation

**Berger, C.** and R. McAdory. US Army Engineer Research and Development Center, Waterways Experiment Station, Coastal and Hydraulics Laboratory, Tidal Hydraulics Branch, CEERD-HE-T, 3909 Halls Ferry Road, Vicksburg, Mississippi 39160. NUMERICAL MODELING OF CURRENTS, SALINITY AND SEDIMENTA-TION IN ESTUARIES. Estuaries have particular defining physical characteristics that require different modeling approaches than might be satisfactory for modeling nearby ocean waters or the rivers connected to the them. Stratified flow and flocculating sediments are two of these physical characteristics that result from the interplay of fresh and salt water in an estuary. Salinity and its movement is central to both of these characteristics. To model the hydrodynamics and the movement of salt in an estuary, especially in estuaries with areas of significant depth, and to enable the development of predictive modeling tools requires three dimensional techniques and physics dominated computer codes. In this presentation, we will present our approach to modeling estuaries to produce hydrodynamic and salinity results.

**Beville, S.**[*] and G.P. Shafer. Department of Biological Science, Southeastern Louisiana University, Hammond, Louisiana. FRESHWATER RIVER DIVERSIONS EFFECTS ON THE GROWTH AND ESTABLISHMENT OF (*Taxodium distichum* (L.) Rich.) IN A BALDCYPRESS-TUPELOGUM SWAMP IN SOUTHEASTERN LOUISIANA. The baldcypress-tupelogum swamps of Louisiana have been degraded in the past 100 years through natural and anthropogenic factors. Sediments and nutrients provided by a diversion would replenish wetlands by decreasing the amount of subsidence and erosion while enhancing ecosystem productivity. The focus of this study will be to evaluate the effects of a river diversion on a dwindling baldcypress swamp in southeast Louisiana compared to an area not influenced by the diversion. To examine the effects of this diversion on the wetland ecosystem, 400 baldcypress seedlings were planted in test plots at both sites testing the affects of fertilizer, herbicide, and herbivore protection on baldcypress growth factors between both sites. This study was scheduled to be conducted for one growing season, but due to drought and herbivory was concluded early. As a result, a second study was conducted in

spring 2000. In this second study three additional sites were chosen, two influenced by the river diversion and one not influenced by the diversion. The same parameters were measured on the growth factors of 70 seedlings at each site. Results from the initial study suggest river diversions are beneficial to swamp systems; weed control using herbicide appears detrimental to seedlings as it lowers redox status and decreases substrate stability. However, both studies demonstrated the need for adequate exclusion devices as herbivory unequivocally explains low survival of seedlings during both studies.

**Blackburn, B.R.**[1*], **C.A. Moncreiff**[1], **B.J. Viskup**[2], **J.D. Caldwell**[1], **T.A. Randall**[1], and **R.K. McCall**[1]. [1]**The University of Southern Mississippi, Institute of Marine Sciences, Gulf Coast Research Laboratory, 703 East Beach Drive, Ocean Springs, Mississippi 39564**[2] **Mississippi Department of Environmental Quality, Office of Pollution Control, South Regional Office, 3002-C Bienville Boulevard, Ocean Springs, Mississippi 39564.** **ANTHROPOGENIC EFFECTS ON PHYTOPLANKTON COMMUNITY DYNAMICS IN THREE COASTAL MISSISSIPPI BAYOU SYSTEMS.** Phytoplankton community structure of three bayou systems in eastern Jackson County, Mississippi, was examined to determine if the effects of coastal development, specifically anthropogenic nutrient loadings and the degree of upland development of the bayou drainage basins, alter phytoplankton community structure. Bayou Casotte, a heavily industrialized area, was compared to two relatively unimpacted areas, Bangs and Graveline bayous. Two sampling sites were selected in each of the bayou systems in order to assess spatial trends in the effects of development along these systems. Nutrient, chlorophyll and phytoplankton samples were collected twice monthly from January through December of 1998 to observe seasonal changes as well as site specific differences. Average chlorophyll $a$ and total cells/liter comparisons in Bayou Casotte were significantly higher ($p=0.05$) than in Bangs Bayou. There were no significant differences between Bayou Casotte and Graveline Bayou for either chlorophyll $a$ or total cells/liter. Bayou Casotte was a predominantly bloom driven system, with lower overall species diversity for the study. Single day species percent compositions within the system were dramatically different in Bayou Casotte. The overall percent composition of the dominant phytoplankton taxonomic division within Bayou Casotte tended to be 20–50% higher than in the Graveline and Bangs systems. Percent composition of phytoplankton groups within these systems were relatively equal. Observed alterations in the phytoplankton community structure are believed to be a direct result of extreme nutrient loadings for the locations sampled.

**Caffrey, J.M.**[1], **T. Chapin**[2], **H. Jannasch**[2] and **J. Haskins**[3]. [1]**Center for Environmental Diagnostics and Bioremediation, University of West Florida, Pensacola, Florida,** [2]**Monterey Bay Aquarium Research Institute, Moss Landing, California,** [3]**Elkhorn Slough NERR, Watsonville, California.** **USING AN IN-SITU NO3-ANALYZER TO MONITOR NO3-RUNOFF FROM AGRICULTURAL FIELDS IN ELKHORN SLOUGH CALIFORNIA.** The importance of nutrient inputs in regulating marine and estuarine productivity is widely recognized. To understand many of the processes operating within estuaries, nutrient concentrations and physical conditions need to be monitored at a temporal resolution capable of resolving events such as tides, episodic storms (including runoff events) and sporadic biological blooms. Being able to capture these events is of critical importance to develop an accurate picture of nutrient loading as well as understanding the interactions among physical processes, uptake, and regeneration of nutrients. An in-situ NO3- sensor has been deployed at Azevedo Pond in Elkhorn Slough since December 1999. Azevedo Pond is a small tidal pond surrounded by agricultural fields planted in strawberries and flowers. During December 1999, NO3- concentrations varied between 0–30 μm. NO3- concentrations varied with salinity (and temperature) where the highest NO3- concentrations coincided with warm, low salinity water. In January 2000, concentrations exceeded 450 μM following the first rains of the season. Concentrations gradually declined to 80 μM over the remaining 4 days of the deployment and slowly resumed the tidal signature pattern. Concentrations in March decreased throughout the month and showed a distinct tidal signature. During the summer months, concentrations ranged between the detection limits of 0.3 μM and 17 μM, with concentrations still showing a distinct tidal signature.

**Cho, Hyun-Jung**[*] and **M.A. Poirrier, University of New Orleans. Department of Biological Sciences, 2000 Lakeshore Dr. New Orleans, Louisiana 70148.** **RECENT INCREASES OF WIDGEON GRASS,** *Ruppia maritima,* **IN LAKE PONTCHARTRAIN.** Lake Pontchartrain submersed aquatic vegetation (SAV) has been in a state of decline since 1953. However, 1999 surveys have indicated an 18-fold increase in *Ruppia maritima* to levels

that rival historic populations. In 2000, surveys were conducted to determine lake-wide distribution and abundance. These data were compared with data from previous years (1996–1999) by three-way ANOVA with fixed variables of time period, study site, and depth. In 2000, north shore *Ruppia maritima* beds extended from west of Tchefuncte River to Pt du Chien, persisted to a depth of 1.8 m and covered about 1.3 km². In eastern Lake Pontchartrain, it occurred as scattered beds that extended from the Rigolets to South Point. On the south shore it occurred as shallow water patches from Lincoln Beach to the Jancke Canal, but was rare west of the canal. A large bed (*ca.* 0.8 hectare) was present near Lincoln Beach and a small bed was found in Jefferson Parish east of the Causeway. In spite of the increase in *Ruppia, Vallisneria americana* has continued to decline and in 2000 quantifiable beds (0.12 km²) were only found on the north shore between Cane Bayou and Pt. du Chien. Although *Potamogeton perfoliatus* and *Najas guadalupensis* were present in past surveys, they were not found in 2000. The increase in *Ruppia* appears to be related to the increase in salinity and water clarity that has occurred since the passage of Hurricane Georges in 1998. The decline in *Vallisneria, Potamogeton* and *Najas* was probably caused by the salinity increase and competition with *Ruppia*. There was a decrease in *Vallisneria* (92%) and *Ruppia* (30%) from 1999 to 2000 in shallow water on the north shore due to aerial exposure during a low water period.

**Fisher, K.J.**[A,*], **E.A. Spalding**[B,*] **and M.W. Hester. Department of Biological Sciences, Southeastern Louisiana University, Hammond, Louisiana 70402. WETLAND PLANT MESOCOSM INVESTIGATIONS: FLOTANT RESPONSE TO INCREASED SALINITY AND NUTRIENT LEVELS**[A]**, AND COMPETITIVE ABILITY OF *Panicum Hemitomon, Sagittaria Lancifolia* AND *Spartina Patens* TO GLOBAL SEA LEVEL RISE SCENARIOS**[B]. Louisiana's wetlands are being negatively impacted by high rates of relative sea-level rise (global sea-level rise plus subsidence). Increased salinity levels pose a significant stress to the growth and survival of fresh and intermediate marsh vegetation, whereas the effects of increased flooding are less clear. In these studies, we examined the effects of global sea-level rise scenarios (increased flooding and salinity levels) on *Panicum hemitomon, Sagittaria lancifolia, and Spartina patens*. Our previous studies indicate that increases in salinity appear to be detrimental to the overall health of attached *Panicum hemitomon* marsh, whereas some increase in flooding may actually result in greater growth. To assess the effects of increased salinity and nutrient load on *Panicum hemitomon* flotant (floating marsh), we initiated a mesocosm study consisting of a factorial design with two salinity levels (0 and 2.5‰) and low and moderate levels of nitrate and phosphate loading. Photosynthetic results to date indicate a negative salinity effect. A second mesocosm study consisting of a factorial design with four salinity levels (0, 2, 4, 6‰), three hydrologies (-10, 5, 20 cm flood), and four vegetative conditions (monospecific *Panicum hemitomon, Sagittaria lancifolia,* and *Spartina patens*, as well as a community composed of the three species) was instituted this summer. In this study, the effects of salinity, hydrology, vegetative condition, and their interactions on species' stress tolerance, growth response, productivity, and competitive ability are being assessed.

**Franze, C.D.**[*] **and M.A. Poirrier. University of New Orleans, Department of Biological Sciences, 2000 Lakefront, New Orleans, Louisiana 70148. CHANDELEUR ISLANDS SEAGRASSES: HURRICANE GEORGES DAMAGE AND RESTORATION EFFORTS.** The main chain of the Chandeleur Islands supports extensive seagrass meadows in the shallow waters along its western side. On September 28, 1998 Hurricane Georges hit the Chandeleur Islands and produced many deep channel cuts through the main island resulting in scouring and the formation of washover fans on seagrass habitat. Field studies that began in January 1999 were conducted to assess the damage. Seagrasses were absent in areas where washover fans formed large shallow deposits on top of the meadows and where extensive scouring was present. Dense stands of *Thalassia testudinum, Syringonium filiforme* and *Halodule wrightii* occurred in areas where the meadows were protected from channel cut deposits and scour energy. Seagrasses extended from the low tide zone to a depth of about two meters at approximately one mile offshore. *Ruppia maritima* was present near shoreline marshes and a few *Halophyla engelmani* plants were found at intermediate depths. *Thalassia* and *Syringonium* were the dominant species, but *Halodule* was often abundant in shallow water. *Thalassia* and *Syringonium* support the ecological and geological integrity of the Islands by stabilizing sediments and providing essential habitats for shellfish, finfish and waterfowl. Natural recovery of *Thalassia* is typically very slow. In February 2000, we began a project designed to restore seagrasses on non-vegetated washover fans produced by Hurricane Georges. Native seagrasses were transplanted at suitable depths using the "plug" method. As a component

of the project, volunteers were recruited and trained in transplanting procedures and monitoring methods. Volunteer efforts resulted in over 14,000 shoots being installed at five restoration sites. Transplant survival has been good. Very limited natural colonization by *Halodule* has occurred, but no widespread natural colonization by *Thalassia* or *Syringonium* has been observed.

**Hale, J. and T.K. Frazer. University of Florida, Department of Fisheries and Aquatic Sciences, 7922 NW 71st Street, Gainesville, Florida 32653. ABUNDANCE AND DISTRIBUTION OF SUBMERGED AQUATIC VEGETATION FROM AERIAL PHOTOGRAPHS: IMAGE ENHANCEMENT, CLASSIFICATION, AND GROUND TRUTHING.** Photointerpretation of aerial photographs is a common way to characterize land cover over broad geographic areas. Traditional mapping techniques involve a single (or few) experienced analysts tracing polygons around features or categories. An alternative, however, relies on image processing enhancements and classification algorithms to delineate features. While not necessarily appropriate for all applications, this alternative method may offer several potential advantages. First, spatial and thematic accuracy can be improved. Second, images canbe readily reclassified, as most of the processing time (including georeferencing) occurs before classification. We are classifying two sets of 9 x 9-inch 1:24 000-scale aerial photographs along the west coast of Florida, north of Tampa Bay, for abundance and distribution of submerged aquatic vegetation (SAV). We have adapted the well known and frequently used Braun-Blanquet sampling scheme to characterize benthic cover and provide ground truth information. This is a simple index which classifies SAV coverage within a 1-square meter quadrat into five categories: less than 5%, 5 – 25%, 25 – 50%, 50 – 75%, and 75 – 100%. This method provides a rapid and repeatable estimation of cover. A notable advantage to using ground truth data based on this popular index is the potential to use historical Braun-Blanquet data with historical aerial photographs. As with traditionally interpreted photographs, images classified from scanned photographs can be used in change detection; changes in location (spatial) and/or classification (thematic). Our next step is to describe SAV in this area in terms of habitat fragmentation using the Patch Per Unit metric and patch shape analysis using the Square Pixel metric.

**Hastings, R.W. Turtle Cove Environmental Research Station, Southeastern Louisiana University, Hammond, Louisiana. EFFECTS OF DROUGHT-INDUCED SALINITY INCREASES IN THE UPPER LAKE PONTCHARTRAIN ESTUARY: VEGETATION.** Southeastern Louisiana has experienced a significant drought for two years, with annual rainfall amounts of 117 cm (46 inches) in 1999 and 58 cm (23 inches) in 2000, some 50–63 cm (20–25 inches) below normal (152 cm, 60 inches). This reduced level of rainfall and freshwater input to the upper Lake Pontchartrain estuary has resulted in dramatic salinity increases. Salinities in Pass Manchac during the period from mid-1980's to mid-1990's ranged from near fresh in winter and spring up to about 3–5‰ in late summer and fall. During most of 1999 and 2000, salinities remained considerably higher, generally ranging from 5–8‰ during all seasons. Marshes have experienced prolonged periods of excessive drying, but have also been flooded occasionally by these high-salinity waters. Obvious changes in marsh and aquatic vegetation have occurred. Some of these changes are documented in a series of comparative photographs illustrating several sites in the Manchac marshes. The dominant marsh plant bulltongue *(Sagittaria lancifolia)* is now less prolific and stressed. Deer pea *(Vigna luteola)* no longer overgrows the marsh in late summer. Wild rice *(Zizania aquatica)* has virtually disappeared. Several aquatic plants including duckweed *(Lemna minor)*, fanwort *(Cabomba caroliniana)*, and floating waterprimrose *(Ludwigia peploides)* are now rare; as are the usually prolific exotics: alligator weed *(Alternanthera philoxeroides)*, Salvinia *(Salvinia minima)*, and Eurasian watermilfoil *(Myriophyllum spicatum)*. Plants more characteristic of upland areas such as groundselbush *(Baccharis halimifolia)*, marsh elder *(Iva frutescens)*, and southern water-hemp *(Amaranthus australis)* have invaded areas where they have previously been uncommon.

**Hastings, R.W. Turtle Cove Environmental Research Station, Southeastern Louisiana University, Hammond, Louisiana. EFFECTS OF DROUGHT-INDUCED SALINITY INCREASES IN THE UPPER LAKE PONTCHARTRAIN ESTUARY: FISHES.** Southeastern Louisiana has experienced a significant drought for two years, with annual rainfall amounts of 117 cm (46 inches) in 1999 and 58 cm (23 inches) in 2000, some 50–63 cm (20–25 inches) below normal (152 cm, 60 inches). This reduced level of rainfall and freshwater input to the upper Lake Pontchartrain estuary has resulted in dramatic salinity increases. Salinities in Lake Maurepas ranged from near zero to 2.5‰ in 1983-84 when a comprehensive survey of itsfish fauna was conducted. Salinities in 2000 have been

considerably higher, 5.0-7.5‰ during August-October. Trawling at seven stations sampled in 1983–1984 were also sampled in 2000, with the following results. Three species, all of which are marine (silver perch, *Bairdiella chrysoura;* spotted seatrout, *Cynoscion nebulosus;* and striped anchovy, *Anchoa hepsetus*) were collected in 2000, but not in 1983–1984. Bay anchovy (*Anchoa mitchilli*) and Atlantic croaker *(Micropogonias undulatus)* remained the dominant species, but the latter was much less numerous in 2000 than in 1983-84. Other marine species common in 1983–1984 were also reduced in abundance (Gulf menhaden, *Brevoortia patronus;* and sand seatrout, *Cynoscion arenarius*) or not collected at all in 2000 (spot, *Leiostomus xanthurus;* and hogchoker, *Trinectes maculatus*). Two species of freshwater catfish (blue catfish, *Ictalurus furcatus*; and channel catfish, *I. punctatus*) and freshwater drum (*Aplodinotus grunniens*) were also much less numerous in 2000.

**Hoeppner, S.S.**[*]**, J.M. Willis G.P. Shaffer. Department of Biological Sciences, Southeastern Louisiana University, Hammond, Louisiana 70402. PRELIMINARY FINDINGS OF THE FEASIBILITY STUDY OF A FRESHWATER DIVERSION INTO THE MAUREPAS SWAMP—PART I: PRIMARY PRODUCTIVITY OF TREES.** The wetlands south of Lake Maurepas have previously been identified as degraded swamp forests in need of restoration. A freshwater diversion has been proposed to bring a greater load of nutrients, sediments and freshwater into the system. To evaluate the potential effects of the proposed diversion, measures of the primary production of trees and the herbaceous undercover, soil subsidence levels, and various soil characteristics were taken at twenty characteristic study sites within the Lake Maurepas basin. This presentation focuses on the primary productivity of trees in the cypress-
tupelo swamp ecosystem. The measure of the primary production of trees was broken down into the two main components of litter fall and wood production. Soil characteristics examined included soil bulk density, interstitial salinity, pH, redox potential (Eh), soil nitrogen levels, and soil phosphorus levels. The most degraded sites chosen for this study exhibited the highest interstitial salinities measured and were found to have the lowest rates of primary productivity per study plot among all study sites. The most productive sites of this study were interior swamps and those affected by the Amite River Diversion Canal.

**Hunter, J.**[*]**, A. J. Nyman and T. C. Michot. University of Louisiana at Lafayette, Department of Biology, Lafayette, Louisiana 70504 and the National Wetlands Research Center Cajundome Blvd. Lafayette, Louisiana 70503. THE EFFECTS OF MANAGEMENT AND SEASON ON SUBMERGED AQUATIC VEGETATION AT MARSH ISLAND, LOUISIANA.** Management often aims to increase submerged aquatic vegetation (SAV) and therefore support more waterfowl. It is important to understand the seasonal growth pattern of SAV in order to understand the effects of waterfowl herbivory or management on SAV. Therefore, I documented changes in SAV over time and among managed and unmanaged areas. I tested the hypothesis that SAV did not vary over time or among four areas (two which are managed by flap-gated variable-crest weirs). I documented water quality parameters (salinity, temperature, water level, turbidity and nutrients) and tested the hypothesis that these parameters did not differ among the areas. I tried to relate these water quality parameters to SAV abundance. Data collected from October 1998 to May 2000 indicated SAV were generally more abundant in managed areas than in unmanaged areas, percent cover and biomass represent different attributes of SAV abundance, and percent cover was more sensitive than biomass when SAV abundance was low. After accounting for the effects of area and time, only water level and water phosphorus concentration were significantly related to SAV abundance.

**McCall, R.K.**[*]** and C.A. Moncreiff. Institute of Marine Sciences, The University of Southern Mississippi, Ocean Springs, Mississippi 39566-7000. DISTURBANCE-MEDIATED CONTRIBUTIONS TO PLANKTONIC CHLOROPHYLL A BY DISLODGED SEAGRASS EPIPHYTES: A MESOCOSM ANALYSIS.** Seagrasses occur throughout the temperate marine environment and representatives of all of the major algal groups utilize them as a spatially-stable substratum. Recent studies have demonstrated the importance of epiphytic algae as important sources of food for the fish and invertebrate grazers that inhabit seagrass beds. Disturbance events may dislodge epiphytes from the grass blades and suspend loose algal cells in the water column where they may be utilized as food by organisms located beyond the boundary of the seagrass bed. Researchers addressing phytoplankton primary production have frequently used chlorophyll *a* as a measure of algal biomass. A mesocosm experiment was conducted to determine whether planktonic concentrations of chlorophyll *a* subjected to disturbance events were significantly

different than chlorophyll *a* from a control group. Planktonic chlorophyll *a* differed significantly between the control and treatments of different disturbance regimes (Analysis of covariance, $p = 0.001$). Treatments consisting of both biotic and abiotic disturbances resulted in the highest concentrations of chlorophyll *a*.

**Moncreiff, C.A.**, B.R. Blackburn, J.D. Caldwell, and N.M. Opel. The University of Southern Mississippi, Institute of Marine Sciences, Ocean Springs, MS 39566-7000. RECURRENT BLOOMS OF *Alexandrium Monilatum* IN MISSISSIPPI SOUND: A PATTERN FOR THE FUTURE? *Alexandrium monilatum* was first reported in water samples collected in Mississippi Sound in August 1979. Blooms occurred sporadically until 1998; since then, blooms of this dinoflagellate have been documented each summer. Degree and extent of bloom development has differed from year to year; however, a pattern now exists in bloom occurrence. *Alexandrium monilatum* is reported not to produce the saxitoxins associated with related *Alexandrium* species blooms in the northeast. However, mouse bioassays on extracts of *A. monilatum* collected during the 1998 bloom event resulted in deaths of mice receiving extracts intraperitoneally. Toxins associated with this dinoflagellate have not been characterized to date; samples of material from this year's bloom are being used to begin this process. Similar hydrologic conditions may have contributed to conditions conducive to the spread and development of this harmful algal species within Mississippi Sound each of the past three summers. Human impacts on the environment, such as increased levels of nutrients in coastal waters, may also be related to the observed increase in the number of blooms formed by this potentially harmful dinoflagellate species.

**Murrell, M.C.** and F.J. Genthner. US EPA, Gulf Ecology Division, 1 Sabine Island Dr., Gulf Breeze, Florida 32561. email: murrell.michael@epa.gov. SEASONAL DOMINANCE OF CYANOBACTERIA IN PENSACOLA BAY, FLORIDA, USA A study was conducted during 1999–2000 in Pensacola Bay, Florida, USA to characterize the seasonal dynamics of nutrients, phytoplankton, and bacterioplankton. Monthly samples were collected from 5 sites spanning the salinity gradient. Abundances of non-heterocystous chroococcoid cyanobacteria (cf. *Synechococcus, Synechocystis*) became very high (3 X $10^6$ ml$^{-1}$) during the summer months. Based on concomitant chlorophyll *a* analyis and microscopic cell counts, we estimated that cyanobacteria contain 1.75 fg chlorophyll *a* cell$^{-1}$. Using this calibration we estimated that cyanobacteria accounted for up to 5.25 ìg l$^{-1}$ chlorophyll in the upper estuary and accounted for ca. 50% of the total chlorophyll (range 11-74%). Similarly, size fractionated bulk chlorophyll analysis showed that the <5 ìm phytoplankton often dominated the community (70-90%). Flow cytometric analysis of Bay samples from July through October 2000 revealed two distinct communities of cyanobacteria based on their fluorescence characteristics. One type was characterized by strong orange fluorescence under blue excitation (488 nm) suggesting cells rich in phycoerythrin (PE). The other type exhibited deep red fluorescence when excited with a red excitation (610 nm) suggesting cells rich in phycocyanin (PC). The distributional patterns clearly show that PC-rich cells dominated in the upper estuary, while the PE rich cells were more abundant in the lower estuary. In the near-freshwater tidal reach of the Escambia River, abundances were typically one or two orders of magnitude lower than in the nearby estuary suggesting that these are marine cyanobacteria. Ongoing studies are directed at better understanding the factors controlling their abundance and distributional patterns, including the potential roles of grazing and nutrient limitation.

**Murrell, M.C.**, R.S. Stanley, E.M. Lores and D.A. Flemer. US EPA, Gulf Ecology Division, 1 Sabine Island Dr., Gulf Breeze, Florida 32561. email: murrell.michael@epa.gov. MICROZOOPLANKTON GRAZING AND NUTRIENT BIOASSAY STUDIES IN PENSACOLA BAY: THE ROLE OF TOP-DOWN AND BOTTOM-UP CONTROLS. To better understand the causes and consequences of nutrient over-enrichment (eutrophication) in Gulf of Mexico estuaries, we examined roles of grazing and nutrient limitation in Pensacola Bay. One consequence of eutrophication is altering the function of plankton food webs; the basis of the marine food chain. Such an alteration can have cascading effects on an ecosystem and result in multiple negative impacts including loss of habitat and loss of human resource use. Micro-
zooplankton grazing and nutrient limitation studies were conducted at 2 sites on 5 dates from December 1998 to September 1999. The grazing experiments examined the potential of top-down control on primary production, while the nutrient limitation experiments examined bottom-up controls. The grazing experiments measured changes in net phytoplankton growth in treatments with varying numbers of microzooplankton predators. Preliminary results

suggest that microzooplankton often exerted a significant control (46% to over100% of production) on phytoplankton growth. The nutrient limitation experiments measured the growth of phytoplankton in treatments with varying nutrient additions. Those results suggest that phosphorus may limit primary production at certain times of the year. Combining these results allows a means to evaluate the relative importance of top-down and bottom-up controls on primary production.

**Nyman, J.A.,** **J.D. Foret, G. Melancon, T.C. Michot, T.J. Schmidhauser\*, A.K. Burcham\*. \*Department of Biology, University of Louisiana at Lafayette, Lafayette, Louisiana 70504, National Marine Fisheries Service, Lafayette, Louisiana 70504, Rockefeller Wildlife Refuge, LDWF, Grand Chenier Louisiana 70643, National Wetlands Research Center, USGS, Lafayette, Louisiana 70506.** **PRELIMINARY STUDIES OFBROWN, BRACKISH MARSH.** Rapid dieback of ~50% of saline marsh in southeastern Louisiana garnered much attention. We show that large portions of brackish marsh at Rockefeller Refuge in southwestern Louisiana also experienced rapid dieback. Foret noted total dieback at 3 of 6 *Spartina patens* dominated sites between March and May, 1999. Michot estimated via aerial survey that ~30% of unmanaged *S. patens* marsh at the Refuge was brown in August 2000. In Oct. 2000, Melancon and Nyman visited Foret's sites and observed lower salinity (28‰ vs. 31‰) and higher pH (6.0 vs. 5.2) associated with healthy sites. Burcham and Schmidhauser isolated more fungal types from brown plants than green plants and observed more rapid fungal growth from brown spots than from green portions of leaves from brown plants. We plan to test if soil conditions likely to have occurred during the recent drought (high salinity, sulfides, and acidity) increased plant susceptibility to fungal infection.

**Opel, N. M.,** **W. Grater, C. A. Moncreiff, and J.D. Caldwell. The University of Southern Mississippi, Institute of Marine Sciences, Department of Coastal Sciences, 703 East Beach Drive, Ocean Springs, Mississippi 39566-7000.** **A PRELIMINARY ASSESSMENT OF GENETIC VARIATION AMONG AND WITHIN POPULATIONS OF *Halodule wrightii* IN THE NORTHERN GULF OF MEXICO.** We began a preliminary assessment of the genetic structure of *Halodule wrightii* in the northern Gulf of Mexico using random amplified polymorphic DNA (RAPD-PCR) analysis. Like many seagrasses, *H. wrightii* depends primarily upon vegetative as opposed to sexual reproduction; therefore, *H. wrightii* populations could display low levels of genetic diversity, and may even consist of one individual clone. Other studies have suggested that populations with low genetic diversity may not adapt as fast as populations containing higher genetic variation. To assess genetic diversity, RAPD primers prepared by the University of British Columbia (UBC) were screened for the generation of bands with *H.wrightii* DNA. These bands indicated that the primer annealed to a number of sequences in the template DNA. We found that *H. wrightii* produced bands for 10 of 35 UBC primers examined. Additional UBC primers will be screened and polymorphic banding patterns established. In addition to RAPD-PCR analysis, direct DNA sequencing utilizing internal transcribed spacer (ITS) sequences may also be employed in order to determine the genetic composition of *H. wrightii* populations. Once the amount of genetic disparity among and within populations of *H. wrightii* is quantified, conservation measures can be evaluated. If some populations display low disparity, transplants from local donor beds could increase variation within these populations. By evaluating the genetic composition of *H. wrightii* populations, improved management options can be determined.

**Parsons, A.C.\*,** **J.M. Willis and G.P. Shaffer. Department of Biological Sciences, Southeastern Louisiana University, Hammond, Louisiana 70402.** **PRELIMINARY FINDINGS OF THE FEASIBILITY STUDY OF A FRESHWATER DIVERSION INTO THE MAUREPAS SWAMP- PART II: HERBACEOUS SPECIES COMPOSITION.** In Louisiana, freshwater river diversions have been proposed as a tool for restoration of degraded wetlands. The wetlands associated with Lake Maurepas in southeastern Louisiana are an example of a degraded system that could benefit from this type of restoration. To investigate the potential benefits of a freshwater river diversion into Lake Maurepas, 20 sites were established within thesouthern Maurepas basin. Within a site, two 625 m² stations were randomly created, and within each station, four 4 m² plots were established. Two of these 4 m² plots were fertilized with time released fertilizer to mimic the nutrient input from a 2000 cfs diversion of the Mississippi River. Percent cover was recorded in all plots in the late Spring and in the Fall of 2000. In order to estimate herbaceous productivity, two clip plots were collected from all 160 plots in the late Spring and Fall of 2000. In addition to vegetation data, soil cores and bulk density cores were collected to determine such soil parameters as interstitial soil

salinity, sulfide, pH, percent soil moisture, and bulk density. Although some of the data have yet to be analyzed, some trends are apparent. As basal diameter of the forest canopy increases, percent cover decreases. Fertilized plots have doubled productivity compared to unfertilized plots; although there is no difference in the soil parameters between the plots. This strongly indicates that the assimilative capacity of the marsh has not been exceeded, and therefore, no algal blooms in Lake Maurepas would be expected from a 2000 cfs diversion. Our research suggests that a freshwater river diversion would be very beneficial to the wetlands of the Southern Maurepas. Without this freshwater river diversion, more than half of the existing wetlands are expected to degrade to open water in the next 5 decades.

**Pasko, E.M.**[1], **J.K. Summers**[1], **R.A. Snyder**[2], **V.D. Engle**[1], **M.C. Murrell**[1], **G.T. DiDonato**[1] **and J. Macauley**[1]. [1]**U.S. Environmental Protection Agency, Gulf Ecology Division, 1 Sabine Island Drive, Gulf Breeze, Florida 32561.** [2]**University of West Florida, Department of Biology, 11000 University Parkway, Pensacola, Florida, 32514.** **THE EFFECT OF PRECIPITATION ON ORGANIC CARBON COMPONENTS IN BAYOU TEXAR, FLORIDA.** This study examined the relationship between precipitation and organic carbon in Bayou Texar, part of Florida's Pensacola Bay system in the northern Gulf of Mexico. Weekly samples were collected from five stations between March to June, 1999. Additionally, samples were taken before, during and after rain events throughout the sampling period using an autosampler. Particulate organic carbon (POC), dissolved organic carbon (DOC), chlorophyll (chl *a*), and nutrient (PO4-P, NOx-N, NH4-N) data were analyzed to examine the effects of storm water from rain events. During this study, rainfall and runoff from individual rain events replaced between 1–8% of the total bayou volume. Regression analysis was used to identify relationships between physical and chemical components in the system. Although pulses of POC, DOC, and nutrients can be detected in the bayou during rain events, results suggest that each component is quickly diluted. Overall, rainfall and runoff had no consistent measurable impacts on the carbon concentrations in Bayou Texar over daily to monthly temporal scales. Nutrient levels suggest that Bayou Texar was nutrient replete during the entire sampling period, implying that nutrient additions from rainfall and runoff did not stimulate phytoplankton growth. The distribution of NOx-N along the salinity gradient suggests nutrient enrichment from terrestrial sources, but storm water additions during the study period could not account for this enrichment. Increases in both POC and Chl *a* were strongly correlated with seasonal increase in surface temperatures and were also independent of storm events. Future studies will determine if the carbon cycle in Bayou Texar is seasonally driven over an annual scale period.

**Thomson, D.**[*1], **A. McCorquodale**[2] **and G. Shaffer**[1]. [1]**Southeastern Louisiana University, Department of Biology, Box 10736 Hammond, Louisiana 70402;** [2]**University of New Orleans, Department of Civil Engineering, New Orleans, Louisiana 70148.** **SPATIAL VARIABILITY OF SOIL WATER PROPERTIES IN AN ESTUARINE OLIGOHALINE MARSH UNDER THE INFLUENCE OF MESOHALINE CONDITIONS.** The spatial variability of soil salinity under the influence of drought was investigated on an estuarine marsh island in the Lake Pontchartrain Basin, Southeastern Louisiana, USA. Habitat changes during the last 100 years, after deforestation due to lumbering, indicate a trend towards increasing salinity and flooding. These wetlands historically received freshwater, sediment, and nutrients from the Mississippi River until the arrival of Europeans who closed its local distributary, Bayou Manchac, and have slowly eliminated periodic crevasses by maintaining mainline levees throughout the area. Marine inputs to the estuary have increased with the opening of the Mississippi River Gulf Outlet and Inner Harbor Navigation Channel. Reforestation efforts in the area have been unsuccessful. Over 100 dipwells were installed radially at 100-meter intervals, in eight compass directions over the entire 4 square-kilometer island. Soil salinity varied both spatially and temporally. Spatial variability may be attributable to variations in elevation, horizontal exchange with tidal slews, vertical exchange with surface water, and soil permeability. Data suggest that areas isolated from exchange accumulate more salts than areas afforded exchange. Temporal variability was attributed to variations in estuarine salinity and climatic factors. Data suggest that current low precipitation amounts are not sufficient to reduce soil salinity. It would be a mistake to attribute current trends and restoration failures to these hydrologic modifications alone; trends must be assessed within both the framework of historical system dynamics, current climatic conditions, and anthropogenic modifications.

**Willis, J.M.**[*], **M.W. Hester, G.P. Shaffer, D.J. DesRoches and S. Miller**. **Department of Biological Sciences, Southeastern Louisiana University, Hammond, Louisiana 70402.** **PROCESSED DRILL CUTTINGS AS PO-**

**TENTIAL SUBSTRATES FOR WETLAND CREATION: AN OVERVIEW OF SOUTHEASTERN LOUISIANA UNIVERSITY'S RESEARCH.** Louisiana experiences one of the highest rates of wetland loss in the world, which is largely driven by the subsidence of deltaic sediments. To successfully create wetlands in much of coastal Louisiana, sediment must be added to counteract the effect of subsidence. Processed drill cuttings are a potential source of sediments that maybe used as wetland substrate. Three intensive mesocosm level studies conducted at Southeastern Louisiana University have examined the suitability of processed drill cuttings as a substrate for freshwater and saline wetland vegetation. All three studies were factorial designs (four substrates including two drill cuttings types: A and B, three hydrologies, and six species treatments) in which interstitial metal concentration, interstitial pH, soil redox, photosynthetic rate, and biomass partitioning data were collected. Plant tissue metal concentrations were also measured in the first and third year studies. Plants in drill cuttings A typically grew as well or better than plants in other substrates, including the control, throughout all studies. Under freshwater conditions, plants grown in drill cuttings B tended to be reduced in growth compared with plants grown in other substrates. This is likely a result of the alkaline pH drill cuttings B demonstrated under freshwater conditions (~10.0). However, under the three saline conditions of the third study, the pH of drill cuttings B was lowered to ~8.1, and photosynthesis was equal or higher than the control. Vegetative uptake of most metals was low for both the first and third year studies. Overall, these studies have demonstrated the capacity of processed drill cuttings as suitable substrates for plant growth under the correct environmental conditions. However, further refining of the processing technique may be required for processed drill cuttings to truly become a viable option for wetland creation.

**Woodley, C.M.\* and M.S. Peterson. Department of Coastal Sciences, Institute of Marine Sciences, The University of Southern Mississippi, Ocean Springs, Mississippi 39564.** **CAN WE QUANTIFY INCREASED PREDATION STRESS DUE TO HABITAT LOSS?** Recent research has documented that fishes associated with submerged aquatic vegetation (SAV), shoals and other aquatic structure may benefit from improved feeding or reduced predation risk. The loss of these structurally complex habitats may increase individual stress levels of small fishes by the increased "perception" of predation threat. Studies have shown that stress, whether natural or anthropogenic, diverts metabolic energy away for normal activities (i.e., growth and reproduction). The objective of this study was to quantify responses associated with the "perception" of predation threat using metabolic rate, cortisol concentrations, behavior, and growth. We quantified individual weight-specific metabolic rate of the prey fish (longnose killifish, *Fundulus majalis-similis*) exposed to a predator (sand seatrout, *Cynoscion arenarius*) using flow-through respirometry. Three treatments (no habitat, artificial SAV, and a blind control) were randomly assigned to experimental respirometers around a central experimental arena where the predator was housed. The routine oxygen consumption of the longnose killifish (n = 8) was found to be significantly different among treatments ($F = 11.277$, $p = 0.00$). Bonferroni pairwise comparisons showed that the killifish routine oxygen consumption in the no habitat treatment was significantly higher than both the artificial SAV treatment ($p = 0.002$) and the control ($p = 0.001$). There was no significant difference in routine oxygen consumption between the artificial SAV treatment and the control ($p = 1.000$). We concluded that longnose killifish fully exposed to a predator have a greater routine oxygen consumption rate than the killifish partially exposed to a predator and the killifish that were not exposed to a predator. From these results, we can infer that the killifish fully exposed to a predator underwent an increase in metabolism due to perceived predation threat. In addition, these results suggest that SAV plays an important role in the mediation of prey-predator relations.